

MEDIUM-CAPACITY AIR MOTOR PILOT PLANT
WITH HYDRAULIC ENERGY ACCUMULATION BY PUMPING

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Renzo Vezzani

Professor of Engineering of the High Council of Public Works

The exploitation of wind energy has so far met insurmountable difficulties from the aerodynamic viewpoint, mainly through the erroneous direction taken from the beginning in constructing the air motor and its supports, which first tended toward catching the greatest area possible in the air column oriented in the horizontal plane, and secondly, toward raising this catchment as high off the ground as possible for the purpose of obtaining greater velocity and regularity of the wind.

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The first tendency, together with the necessity of making the air motor orientable to the different wind directions, increased the diameter of the blades to such an extent, and gave rise to such complex problems of mechanics and assembly of the various devices as to multiply the failures of the first attempts, and to foster in builders and technicians an unjust distrust of this system of electrical energy production, that one can say that it is still in the initial stage of study and research.

The second tendency, which further complicates the solution of the preceding problems through the dynamic actions imparted by the wind on tall metal structures and the vibrations due to the rotating mass atop the supports, makes the adoption of this type of plant absolutely prohibitive for a country as poorly endowed in iron as Italy, and, in any case, it exposes the most delicate sections of the wind-electric system to the violence of storms multiplied by the great height from the ground and by the great extension of the air motor, which can hardly be lowered, in such sudden occurrences, to minimum safety requirements.

*Numbers in the margin indicate pagination in the foreign text.

If one recognizes in these weaknesses of the present air motor structures the essential cause of the delay, otherwise inexplicably interposed in the utilization of an energy which, after that of the sun, is the greatest in nature and, moreover, completely free, one must necessarily work out and adopt the instructions on orientation which are briefly summarized here below:

1) Concentration in space of a force which is extremely diffuse in nature, as the wind is, in such a way as to substitute for the great catchment areas of the air motors exposed to free air, which are by necessity light and orientable to the wind, small, high-speed air motors which are completely protected and fixed in space for direct connection with the electric generator.

2) Construction of wind catchment structures which are fixed in space and properly anchored to the ground in such a way as to make the solution of the problems of stability, safety and the economy of the plants identical to the solution which is used for tall buildings, aircraft hangars and so on, and to enable the adoption of structures suitably designed to resist every aerodynamic activity.

3) Reduction to the minimum of the orientable parts of the wind-electric plant for catching the various wind directions when, generally speaking, it is not possible to exploit an air current which is unidirectional or which is in two directions of the same orientation, in which case the whole plant is fixed in space.

4) Improvement of the efficiency in the transformation of wind energy into electric by means of the intubation of the air motor.

The first and fourth requirements are fully satisfied by the instructions developed in several patents held by the author¹,

¹R. Vezzani, Italian patent, "Device for multiplying the power of air motors in large wind-electric power stations."

which involve adopting for the catchment of wind energy and for the intubation of the air motor a Venturi tube with the forward section exposed to the wind and the air motor mounted in the contracted section, so that the slightly flaring truncated cone of the rear section works to diffuse the current, causing a strong depression in the passage, thereby increasing the velocity of the air current which is calculated to be two to three times that of the air hitting the forward section.

Its orientation to wind direction is achieved with a rotating gear which automatically joins to the contracted section two or more fixed inlets of a series of large wind-tunnels arranged in a circular manner and directed toward all sectors of the horizon. With this solution, which responds satisfactorily to the second and third requirements, it becomes possible for an air motor plant of this type in any mountainous location to be exposed to wind from every direction, as in the case which will be discussed next as an example.

But in special cases, such as in a saddle over a ridge separating two basins with a distinct difference in pressure and temperature, /399 or in a deep valley with mountain glacier, etc., it might be possible to single out a locality swept by unidirectional winds, and the air motor plant could be entirely fixed in space, at best with an air motor with reversible blades for catching air currents in two opposite directions of the same orientation.

However, with a subsequent patent² the author carried out some very important improvements in the space and time accumulation of wind energy, aimed at obtaining a greater value in the k factor for the multiplication of the difference between internal and external pressures (on which depends the velocity in the contracted section), and at enabling the storage of extra wind energy for later use in

²R. Vezzani, Italian patent, "Improvements in wind-electric power plants for the accumulation in space and time of wind energy."

periods of calm or of weak winds.

The first objective is attained either with the adoption of two or more coaxial Venturi tubes, or with the addition of static devices at the outlet of the diffuser which, by increasing the depression in the neck of the tube, increases the velocity at the inlet of the tube by up to one and a half times that of the wind. If one adds to this suction effect that of the improvement of the efficiency of wind energy transformation achieved by intubation of the air motor, which would thus function as a Kaplan turbine (with small loads corresponding to weak winds, which require better utilization, it is calculated that it may be possible to reach 100% of the load on an air motor exposed to free air), one arrives at a reduction in the air catchment diameter of the air current which is calculated to be about 50%.

For the second objective, various solutions were examined, among them: that of lifting water from a lower basin to an upper one with a pump according to the systems already noted and extensively applied in hydroelectric power plants in Europe and America.

In the specific case treated in the present report, which is to say a wind-electric plant of medium capacity (500 kW) built on an island considerably removed from the continent (the island of Giglio in Grosseto Province), the method adopted was the lifting of sea water into a reservoir obtained by damming up a small valley of granite rock formation shown in the topographic maps of Figs. 7 and 9.

But other solutions were also taken into consideration, such as the accumulation of wind energy in the form of compressed air, utilized later on a gas turbine, or the production, with the extra energy and by means of electrolysis of the water, of hydrogen which is then compressed in cylinders and utilized later in special diesel motors.

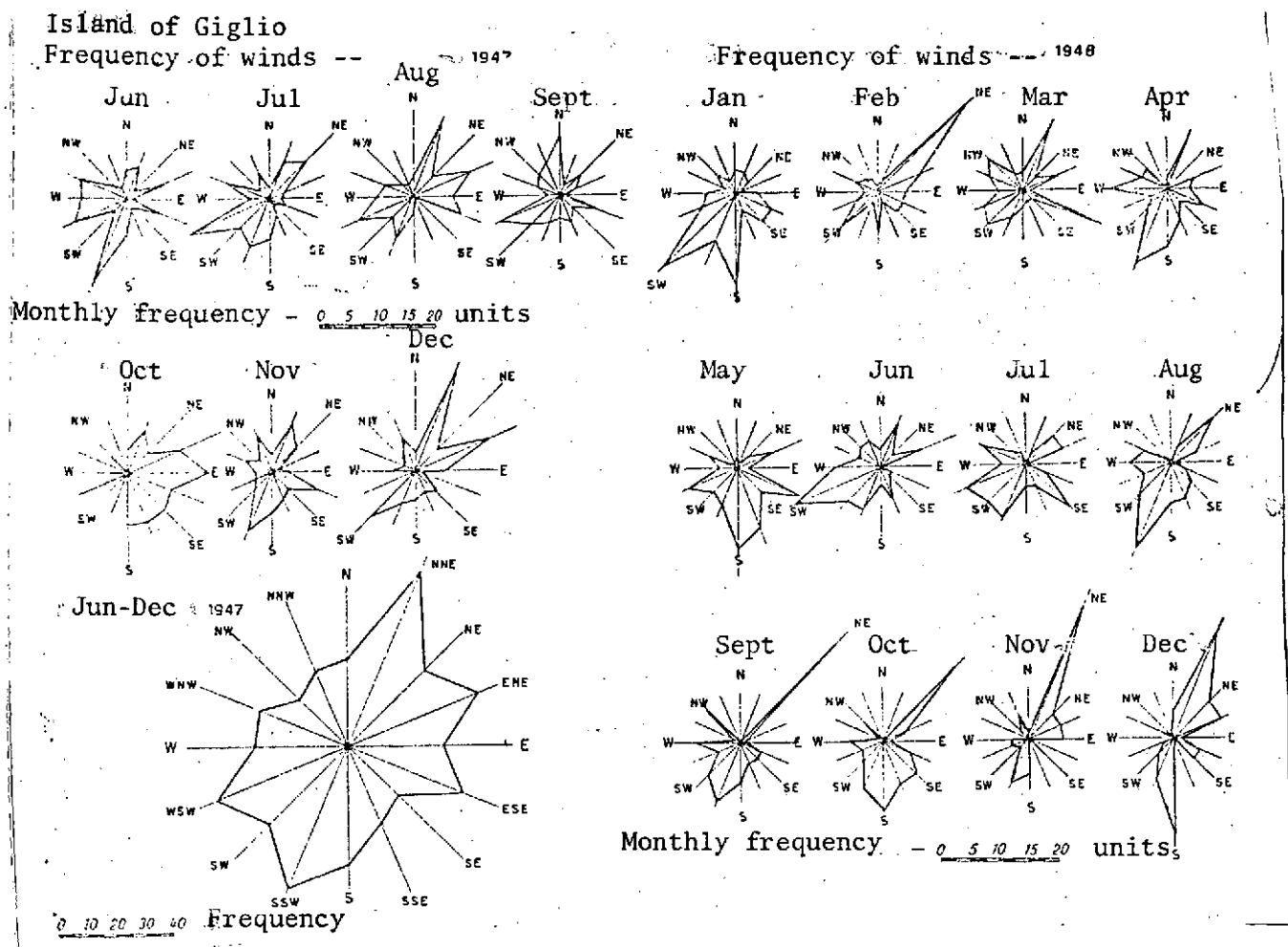


Fig. 1. Frequency of winds on the island of Giglio.
Giglio Castello Observatory.

These systems, naturally more complex and requiring more precise execution, are still in the study stage, and do not constitute the purpose of the present report, although they are particularly suitable for the special case of a power plant completely isolated from the electric power distribution network. They offer -- especially the first one -- the most economic long-term solution for the specific problem under consideration.

But the solution of pumping and accumulation of water is also identified with the solution of the problem which arises in the majority of the possible cases of wind-electric plants:

namely, that of feasible integration into a distribution network for energy input according to the already-known methods of continuous current of constant voltage produced by the action of converters for transformation into alternating current of constant voltage and frequency, or the direct production of alternating current with these characteristics.

In the example of the wind-electric plant under consideration, which, because it is the first of its kind in the whole world, was defined, according to the American terminology, as "pilot," this solution was adopted, however, as it is simpler and more easily extendable to the generality of hydroelectric plants to be integrated with the exploitation of wind energy, according to the system of hydraulic accumulation through pumping already realized on a vast scale.

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In the report, the criteria will be listed which were followed in the study and determination of the wind behavior at a site on the island selected for the wind-electric power station on the basis of surveys conducted by the Giglio Observatory.

Anemological Surveys and Choice of the Power Plant Site

The time period for which systematic surveys of the velocity of the wind and its prevailing directions was conducted at the observatory is restricted to the second half of 1947 and the whole of the year 1948, the period of the start of preliminary studies. Nevertheless, the surveys were continued for the whole of 1949 and the first half of 1950, and their results will possibly be taken into account in the definitive project (Figs. 1, 1a and 1b). It is, however, deemed indispensable that a comparison be made between the wind behavior at a nearby observatory, the Orbetello semaphore, the anemometric surveys of which have been conducted for many years (Figs. 2, 2a, 2b and 2c), and the velocities observed in 1948 at the Giglio Castello Observatory, for the

Jan-Dec 1948
0 10 20 30 40 50 frequency

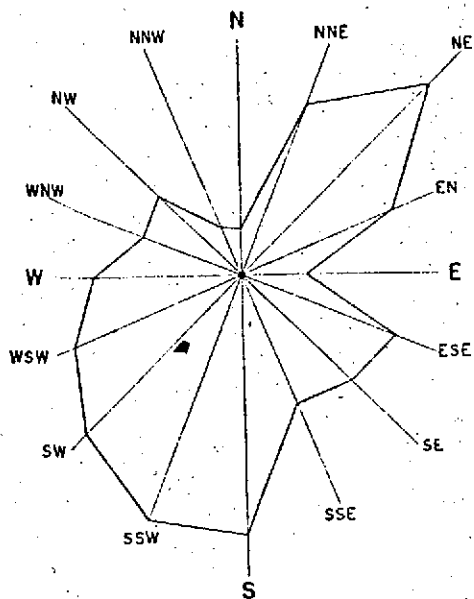


Fig. 1a. January-December 1948; summary of wind frequencies at Giglio Castello Observatory.

purpose of deducing from them the percentages of correction to apply on the latter in order to arrive, with some approximation, at a behavior of the winds for an equal period of time (about 18 years). In doing this, the only hypothesis is that the statistics of the Orbetello semaphore on wind velocities for this period are those up to the 1948 statistics, as the

Diagrams of products of frequencies times average velocities -- 1948

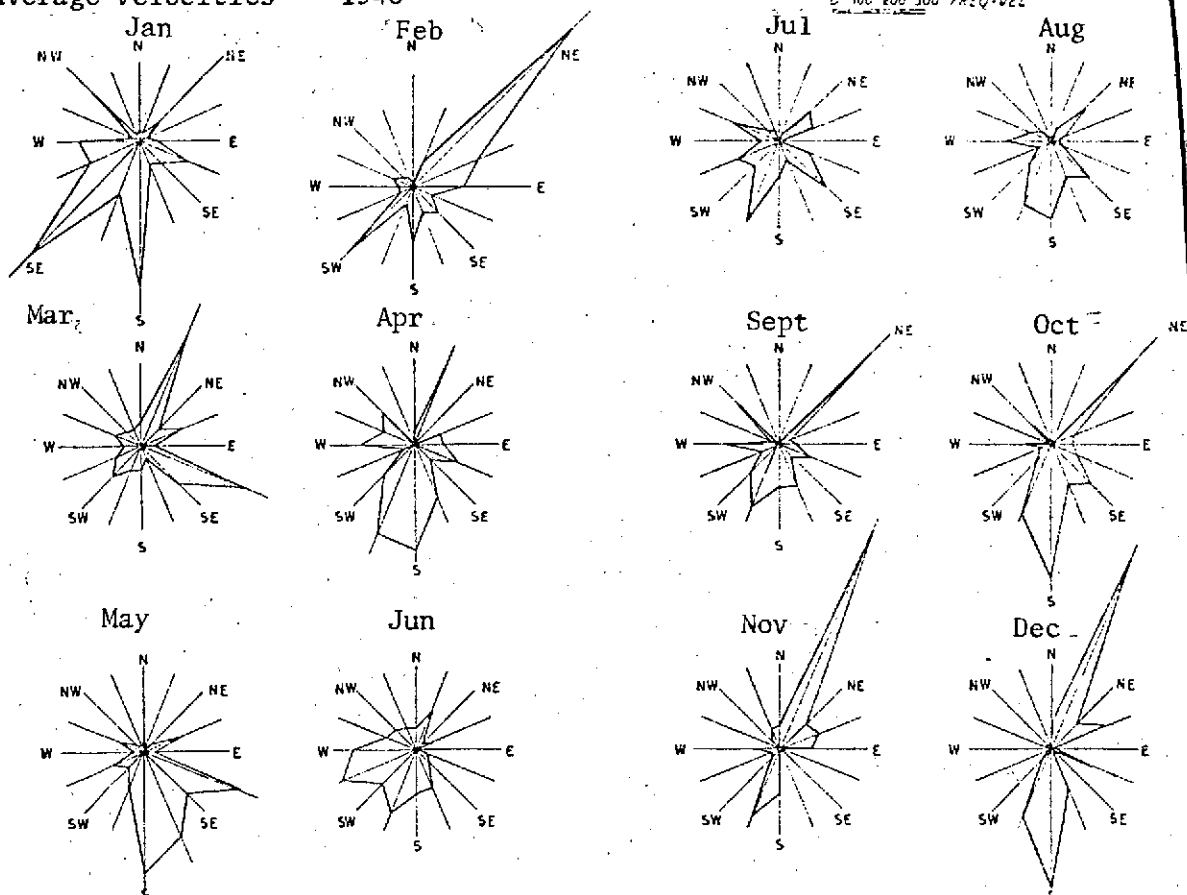


Fig. 1b. Monthly polar diagrams of the frequencies times the wind velocities in the year 1948 at the Giglio Castello Observatory.

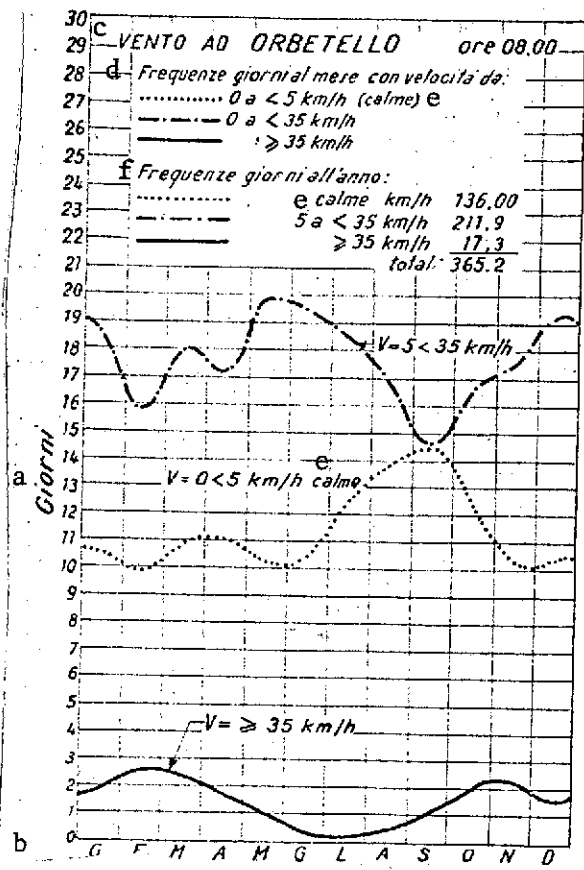


Fig. 2. Frequencies of the average wind velocities at 8 a.m. in the different months and in a year at the Orbetello Observatory over 18 years.

Key: a. Days
 b. Months [G = Jan; F = Feb, etc.]
 c. Wind at Orbetello, 0800 hours
 d. Frequencies of days in month, with velocity of:
 e. Calm
 f. Frequencies of days in year:

percentages by the average velocity of the wind encountered in that direction. In this manner, one can appraise at first glance the relative weight each direction has in the exploitation of wind energy, whether in terms of the direction itself or in terms of the wind velocity in that direction.

statistics of the Giglio Castello Observatory for the same period are to those of 1948. In Figs. 1 and 2 are reported, due to space limitation, only a few of the polar /401 diagrams of the wind frequencies and velocities at the two above-mentioned observatories.

In order to take into account next, in the study of wind energy utilization, the weight which the wind velocity can bring for each direction, we have also traced, apart from the usual polar diagrams of the wind frequencies, diagrams which may be defined as "heaviness" diagrams. These were obtained by multiplying, for each direction, the frequency

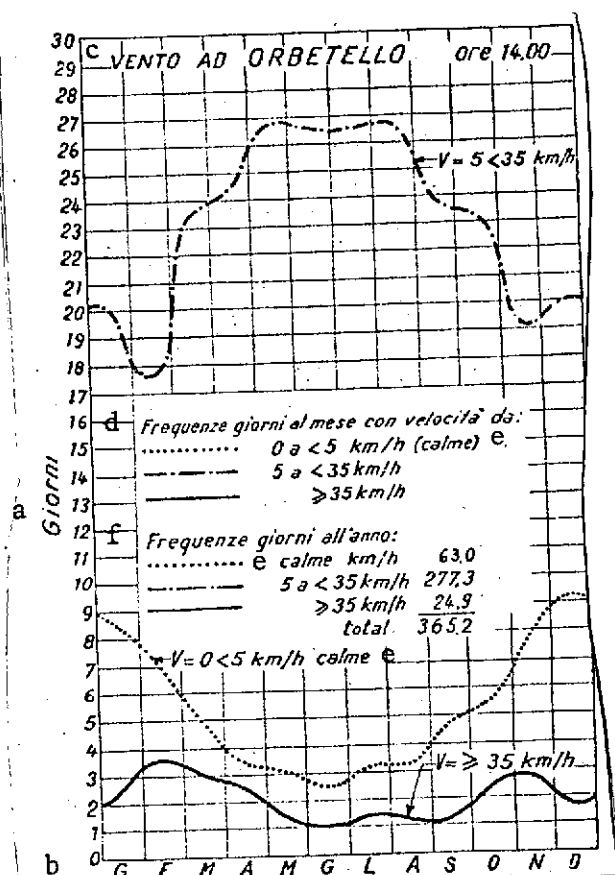


Fig. 2a. Frequencies of the average wind velocities at 2 p.m. in different months and in a year at the Orbetello Observatory over a period of 18 years.

Key: same as Fig. 2.

It is easy to deduce from these weight diagrams that for the location of Giglio Castello it is not possible to adopt a power plant of the fixed-orientation type like the one mentioned above, but instead, it will be necessary to adopt an air-current catchment system which is orientable in all directions.

With this premise, and with the inevitable exclusion of the location of Giglio Castello due to the existence of a town which occupies almost all of the summit (maximum elevation 407 m

above sea level), there only remains the uncertainty of the choice among the three other major hilltops on the island, which are: the Poggio della Chiusa hill with an elevation of 475 m, Mt. Castelluccio with an elevation of 480 m, and the Poggio della Pagana hill with an elevation of 498 m (Fig. 5a).

From the examination of the topographic map of the Military Geographic Institute in Florence, on a 1:25,000 scale, it is easy to see that the Poggio della Pagana, apart from having the greatest elevation, is better exposed to all the wind directions

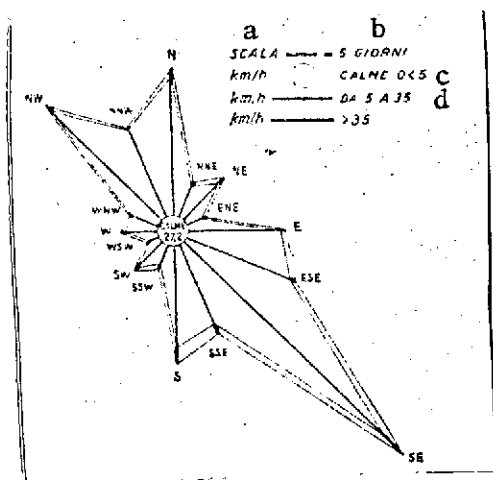


Fig. 2b. Annual summary of the average wind velocities at 8 a.m. at Orbetello over 18 years.

Key: a. Scale
b. Days
c. Calm
d. From ... to

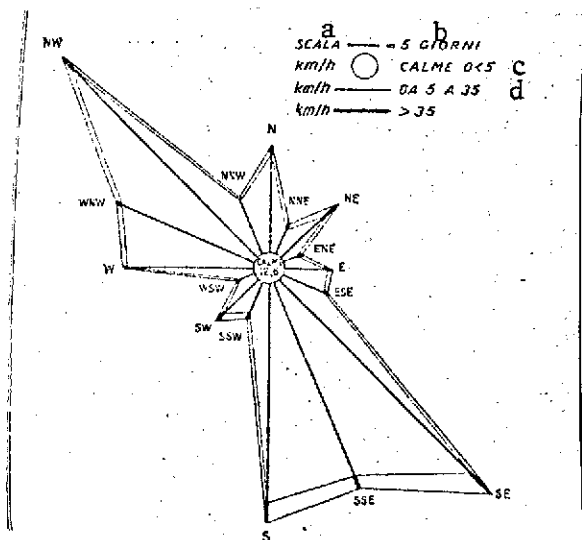


Fig. 2c. Annual summary of the wind velocities at 2 p.m. at Orbetello over 18 years.

Key: Same as Fig. 2b.

except perhaps the northeast, or the so-called "Greek" wind, sheltered partly by the Poggio della Chiusa hill, which, however, being 20 m lower and separated from the first hill by a deep valley, cannot constitute a serious obstacle to air currents.

For the preliminary plan of the wind-electric plant of the island of Giglio, calculation of the available wind energy could be carried out in the aforementioned manner on the accurate anemological data collected at the Giglio Castello Observatory. This would undoubtedly be a precautionary hypothesis, given that the Poggio della Pagana hill is 100 m higher and has better exposure to winds from all sectors of the horizon, except perhaps the northeast.

Potential and Type of Power Plant

With respect to the potential, we will mention that at present, the energy

consumption by private users for light and power is determined by two population centers: Castello del Giglio and Giglio Porto (harbor), as well as by a pyrite mine on the island. From the statistics in Towns of Italy, published by the Central Institute of Statistics, one can count the total population now to be over 5000 inhabitants, distributed as follows: Castello del Giglio 2400 inhabitants, Giglio Porto 1600 inhabitants, and other small centers in the countryside 1000 inhabitants.

In anticipation of the tourism development which will take place on the island of Giglio in the coming years with the construction of a highway network, at present nonexistent, the creation of new population centers on the shores and the construction of scattered villas and houses in the country, an estimate on the future island population of about 8000 inhabitants in the next decade does not seem excessive.

In comparison with the isle of Capri in the state it was in during 1939 and to which, with suitable proportioning, the island of Giglio at the end of the development period could be likened, it would work out that 200 private users will consume 200,000 kWh per year on the island of Giglio. Doubling this consumption to take into account public lighting, a funicular to be built between the inhabited area of Giglio Castello and the landing at the harbor, the town aqueduct which will include a water pumping plant, the use of domestic electric appliances, etc., one arrives at a forecast of 400,000 kWh per year, which is increased during the shift of 8-hour rest periods in the above-mentioned pyrite mine by another estimated 200,000 kWh. This would give a total of 600,000 kWh per year, which corresponds to a capacity of about 200 kW for 8 hours a day.

To this energy quantity required for the daily period must be added what is needed for the 16 hours of the two work shifts at the mine. At present, this consumption is 2000 kWh per day, but

one must take into account the fact that the high cost of thermally-produced electric energy without compensation constitutes a strong limitation on consumption. The estimate that the present consumption will be more than tripled in the 10-year period under consideration is therefore not excessive, if the cost of the kilowatts produced by wind energy could be reduced to half or even to less than the present cost. The power used in the two work shifts would become 300 kW.

Altogether, the daily energy consumption on the island would be:

$$300 \times 16 + 200 \times 8 = 6400 \text{ kWh}$$

Let us now consider the various efficiencies of the machinery interposed, according to the aforementioned scheme, between the air motor and the meter, for calculating the energy to be produced per year.

Efficiency of continuous-current generator	= 0.9
Efficiency of pump for lifting sea water	= 0.7
Efficiency of basin for accumulation of pumped water	= 0.9
Efficiency of turbine driven by full pipe	= 0.8
Efficiency of alternator for alternating power production	= 0.9

The total efficiency for the whole system thus comes out to only 0.4, assuming, as a more unfavorable hypothesis, that it would always be necessary to go through hydraulic accumulation by pumping in order to produce three-phase electric energy of constant voltage and frequency.

The energy required for 1 year will then come out to:

$$\frac{6400 \text{ kWh} \cdot 365}{0.4} = 585 \cdot 10^4 \text{ kWh}$$

In the following table are indicated the duration per year of the various wind velocities grouped in 11 steps, namely from 0 to 2

m/sec, from 2 to 4 m/sec, from 4 to 6 m/sec, etc., up to from 20 to 22 m/sec.

Velocity in m/sec

Duration in seconds per year

0-2	$514 \cdot 10^4$
2-4	$646 \cdot 10^4$
4-6	$725 \cdot 10^4$
6-8	$572 \cdot 10^4$
8-10	$397 \cdot 10^4$
10-12	$183 \cdot 10^4$
12-14	$857 \cdot 10^3$
14-16	$466 \cdot 10^3$
16-18	$438 \cdot 10^3$
18-20	$146 \cdot 10^3$
20-22	$145 \cdot 10^3$

The average values of the wind velocities in the different intervals were thus assumed to be:

0-2	$V_m = 1,35 \text{ m/sec}$
2-4	$V_m = 3,15 \text{ m/sec}$
4-6	$V_m = 5,1 \text{ m/sec}$
6-8	$V_m = 7,1 \text{ m/sec}$
8-10	$V_m = 9,1 \text{ m/sec}$
10-12	$V_m = 11,0 \text{ m/sec}$

etc.

The power output of an air motor with blades exposed to free air has been calculated by the well-known formula proposed by Prof. Betz and used universally in Germany, which gives the theoretical maximum power as:

$$P_{\max} = \frac{16}{27} \rho \frac{V^3}{2} \frac{\pi D^2}{4} \text{ in kgm/sec.}$$

Putting the air density at $\rho = 1/8$ and applying an efficiency coefficient of 0.65 in order to take into account the losses due to imperfections in the construction of the air motor and to the gear system between the air motor and the electric generator (this coefficient is also used universally in Germany on the basis of

wind tunnel tests using calculated and accurately designed models), one arrives at the effective power of the air motor through the following formula:

$$P_e = 0,02 D^2 V_m^3 \text{ in kgm/sec.}$$

Applying to this formula the different values of average wind velocities shown above for each velocity stage, the corresponding powers are obtained:

$$\begin{array}{ll} V = 0-2 & P_e = 49,6 \cdot 10^{-3} \cdot D^2 \\ V = 2-4 & P_e = 0,6 \cdot D^2 \\ V = 4-6 & P_e = 2,68 \cdot D^2 \\ V = 6-8 & P_e = 7,5 \cdot D^2 \\ V = 8-10 & P_e = 14,6 \cdot D^2 \\ V = 10-12 & P_e = 26,8 \cdot D^2 \\ V = 12-14 & P_e = 44 \cdot D^2 \\ V = 14-16 & P_e = 68 \cdot D^2 \\ V = 16-18 & P_e = 100 \cdot D^2 \\ V = 18-20 & P_e = 138 \cdot D^2 \\ V = 20-22 & P_e = 186 \cdot D^2 \end{array}$$

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The energy values obtainable during an average year will be calculated from the above power values, applying to them the corresponding durations of the wind velocities reported earlier, thus obtaining the following expressions as a function of diameter D of the air motor:

V = from 0 to 2 m/sec

$$E = \frac{514 \cdot 10^4 \cdot 49,6 \cdot 10^{-3} \cdot D^2 \cdot 9,8}{36 \cdot 10^5} = 0,695 \cdot D^2 \text{ in kWh}$$

V = from 2 to 4 m/sec

$$E = \frac{646 \cdot 10^4 \cdot 0,6 \cdot D^2 \cdot 9,8}{36 \cdot 10^5} = 10,5 \cdot D^2$$

V = from 4 to 6 m/sec

$$E = \frac{725 \cdot 10^4 \cdot 2,68 \cdot D^2 \cdot 9,8}{36 \cdot 10^5} = 51,7 \cdot D^2$$

V = from 6 to 8 m/sec

$$E = \frac{572 \cdot 10^4 \cdot 7,5 \cdot D^2 \cdot 9,8}{36 \cdot 10^5} = 116 \cdot D^2$$

V = from 8 to 10 m/sec

$$E = \frac{307 \cdot 10^4 \cdot 14,6 \cdot D^2 \cdot 9,8}{36 \cdot 10^5} = 122 \cdot D^2$$

V = from 10 to 12 m/sec

$$E = \frac{133 \cdot 10^4 \cdot 26,8 \cdot D^2 \cdot 9,8}{36 \cdot 10^5} = 133 \cdot D^2$$

V = from 12 to 14 m/sec

$$E = \frac{857 \cdot 10^3 \cdot 44 \cdot D^2 \cdot 9,8}{36 \cdot 10^5} = 102 \cdot D^2$$

V = from 14 to 16 m/sec

$$E = \frac{496 \cdot 10^3 \cdot 68 \cdot D^2 \cdot 9,8}{36 \cdot 10^5} = 86 \cdot D^2$$

V = from 16 to 18 m/sec

$$E = \frac{438 \cdot 10^3 \cdot 100 \cdot D^2 \cdot 9,8}{36 \cdot 10^5} = 120 \cdot D^2$$

V = from 18 to 20 m/sec

$$E = \frac{146 \cdot 10^3 \cdot 138 \cdot D^2 \cdot 9,8}{36 \cdot 10^5} = 54 \cdot D^2$$

The extractable energy for the last velocity stage, from 20 to 22 m/sec, was not calculated to be among those effectively produceable by the air motor, due to the belief that, for this stage, the motor must be protected from the wind action to avoid damage to the machinery.

Adding up the kWh produced per year and equating this anticipated total production to the energy required for the same period of time, as calculated earlier, we obtain:

$$\left. \begin{aligned} 796 \cdot D^2 &= 585 \cdot 10^4 \\ D^2 &= \frac{585 \cdot 10^4}{796} = 7350 \end{aligned} \right\}$$

D = about 86 m

With this air motor diameter, the anticipated energy requirement per year on the island should be satisfied, assuming however that the energy produced is always utilized for pumping sea water.

into the storage reservoir, even if physically it is not all collected in the latter but only derived from the pressure of the full pipe which drives the alternator turbine.

At this point, one may reflect that the greatest wind-electric power plant of this type whose example has existed up to the present was the one built in the USA at Grandpa's Knob in Vermont, with an installed capacity of 1000 kW, with massive steel blades 54 m in diameter. The experience undergone by this plant was not too encouraging. After a period of a year of irregular functioning with only about 1 month of effective use, one of the blades flew off and was later recovered at a distance of about 100 m, while the other blade, already cracked in the hub (which was the breakage point of the previous blade), and continuing to turn unbalanced, seriously damaged the trellis-work, causing its ruin and the subsequent abandonment of the plant by the construction firm which, following this, also gave up the related patents.

It is thus believed that a plant of installed capacity of about twice the one above, built with the same system on an island exposed to sudden sea storms coming from the open on almost all sectors of the horizon, cannot but follow the same fate in a short period of time. Also, the points of breakage of both blades appear to demonstrate that in that case it was not due, as was later maintained, to defects in the fusion of one blade, but to movements or corrosion caused in this critical section that were difficult to overcome.

Nor is it possible to solve the problem of distributing the installed capacity, which, as will be seen, should be at least 2000 kW, among different power plants of smaller capacity which would have to be placed on the three major elevations of the island and would give rise to several generator plants connected with each other by power transmission lines. Having in such a

case to fix the installed capacity at 200 kW and the blade diameter at 30 m for each plant (the maximum size permitted by safety conditions and feasibility at the present state of this type of structure), we would have to have as many as ten plants, subdivided into three groups of three or four plants each, with an absolutely prohibitive total cost and functional complexity.

In this regard, one should recall that a similar solution involving five 200 kW plants at a total capacity of 1000 kW proposed by a Swiss company for the isle of Ischia had to be abandoned due to the recognized difficulty and the nonfeasibility of their realization.

Moving now to the examination of the possibilities offered by the type of wind-electric plant being proposed, it is deemed appropriate to precede it with the following opinion given by Prof. Pietro Teofilato, professor of aerodynamics at the School of Aeronautical Engineering at Rome University:

"In adopting the Venturi tube, one should take into account the attractive effect of the tube, in which, as experiments show, the Venturi accelerates the air which is introduced at its mouth to the extent that, if a Venturi is applied at the efflux of a tank, the capacity becomes greater than that which would be handled by a simple hole, even to the extent of 1.5 times (Hand- /404 buch der Physik [Physics Handbook], Vol. VII, Berlin, 1927, p. 192). Calix de vexus amplius rapit [a sloping cup holds more), as the Roman Sextus Julius Frontinus put it.

"It is concluded that the power produced at the mouth of the Venturi is greater than that which presents itself over an equal area which one may imagine in space that is free of obstacles or tubes. Naturally, under the principle of energy, greatest power should be obtained at the loss of pressure and kinetic energy of the current outside the tube, which in fact undergoes a slowdown.

"On the other hand, the fan too has an inherent slowdown effect all the way to the infinite upstream. This effect is conspicuous at the point where, if the fan blades move freely in space and are calculated to achieve the maximum exploitation of the power made available by the wind, the infinite upstream velocity V_0 is reduced on the fan-blade disk to a little over $2/3$ of V_0 , in contrast to what is observed for a propulsive airscrew, which instead accelerates the current from infinite upstream to infinite downstream.

"Since the Venturi airfan system is involved here, one can assume that for an infinite upstream velocity of 6 m/sec (equal to the average velocity given by the anemological surveys available for Giglio island), the entry into a Venturi without an airfan (having accepted the ratio of 1.5 given in the volume cited above) would take place at a velocity of 9 m/sec, and that the fan blades in turn lower the velocity to 7 m/sec.

"The theoretical study which was undertaken will corroborate the presuppositions in determining more precise data; however, it is to be remembered that they are not very far from reality. The effective velocity of 7 m at the mouth corresponds, through the theorem of continuity, to 28 m/sec for an area having half the diameter of the mouth, as is anticipated for the tube neck, so that, if we place the load loss at 3 m/sec from the inlet to the neck, the resulting velocity at the fan-blade disk becomes 25 m/sec. An airfan of a 10-m diameter under the scheme being examined, one that would absorb the maximum power, could supply -- if its efficiency is equal to unity -- a power of:

$$\frac{8}{27} \pi R^2 V_0^3 = \frac{8}{27} \pi \frac{1}{8} \left(\frac{10}{4} \right)^3 25^3 \text{ kW} = 145 \text{ kW.}$$

"In fact, in the maximum power formula, the velocity used is that of infinite upstream. Here the upstream velocity is taken as that at the mouth of the Venturi, which was transformed into that which occurs at the disk behind the convergence of the tube.

"The above-mentioned calculation considers air as incompressible. In reality, acceleration in the forward portion (converging) of the Venturi is accompanied by a gradual process of depression, little by little as it approaches the neck, and then by a subsequent diminution. The opposite takes place in the portion behind the neck (diverging) where, with recompression, condensation takes place.

"If one wishes to examine the total error made in considering the density as constant, one must turn to the following formula in which the subscript zero refers to the inlet mouth of the Venturi, the subscript 1 to the neck section, and 2 to the outlet mouth:

$$p_0 - p_1 = h \frac{\rho}{2} V_1^2$$

where the coefficient h is linked to the Reynolds number R by the relationship:

$$6 \log_{10} R - 1,155 \quad h = 14,986$$

which is valid at least up to $R = \text{about } 10^7$. In the case in question, where the diameter is 10 m and the velocity 25 m/sec, it turns out that $R = 2.5 \cdot 10^6$, where $h = 14$ and thus $p_0 - p_1 = 526 \text{ kg/m}^2$, corresponding to about 5.4% normal pressure.

"Assuming next an adiabatic condition, as is rightly accepted in this case, and having taken into account the approximate relation which links the change in pressure Δp to the change in density $\Delta \rho$

$$\frac{\Delta p}{p} = 1,4 \frac{\Delta \rho}{\rho}$$

we get $\Delta\rho/\rho = 3.8\%$; thus, in the phenomenon under study, the change in density can be regarded as negligible.

"The power of 145 kW found above is then reduced to take into account the efficiency of the airfan. If the shape of the fan blades and their attachment is properly calculated for a functioning relationship of $\gamma = V_0/nD$ (V_0 is the velocity at infinite upstream, n the number of revolutions, and D the diameter of the fan blade) corresponding to the prevailing wind, one can attain an efficiency which will work out to 80% or more in absorbing the maximum power, and we get an output of $0.8 \cdot 145 = 116$ kW. This, as we have said, refers to a mouth 20 m in diameter for which, if a power of 500 kW is desired, a mouth of 1600 m^2 is required, corresponding to a diameter of 45 m.

"Some reflection is due in this regard. A mouth of 1600 m^2 involves a power which, under the formula $\frac{1}{2}\rho V_0^3$ kgm/sec, or even $\frac{1}{1600} V_0^3$ kW per m^2 , and therefore, for the velocity of 7 m/sec, is $0.214 \cdot 1600 = 342$ kW.

"This result, at first glance disconcerting from the energy viewpoint, is explained by observing that the power of 342 kW is kinetic power, which is not the only one which is working. In fact -- and this is the value of the Venturi tube -- one observes a loss of pressure in the subsequent pressure work in the funnel of the converging portion, work which will be recovered in good measure in the diverging funnel, if the airfan were not present. The recovery, which occurs in the diffusor, is completed by ejection out of the tube, in that the air outside the latter is, in the proximity of the outlet opening, faster than that which flows out of it; conversely, in the case of water which flows from a container through a Venturi, it is practically the action of gravity which accelerates the flow in a falling state in air."

In order to put this recovery action into numerical form, one can refer to the analogous phenomenon which is observed in plants using downward-flowing water when the falling sheet of water from the sluice gates is introduced at the outlet of the diffusor.

Following the method of Prof. L. Conti for calculating the ejection effect of discharge from turbines, one can assume for simplicity's sake that this takes place with a velocity V_0 which prevails in a transverse downstream flow. Let Q_t be the capacity passing through the turbines and Q_a be the auxiliary capacity. The reflux r takes place for the whole mass of water, and thus it is reduced with respect to the reflux which would occur for the velocity V_1 acquired by the auxiliary mass, to the extent of:

$$r = \frac{Q_a}{Q_a + Q_t} \cdot \frac{V_0 (V_1 - V_0)}{g} \quad \left| \begin{array}{l} V_1 = \eta \sqrt{2g \sqrt{\Delta h + r}} \end{array} \right.$$

where

in which $\eta < 1$; Δh is the jump between upstream and downstream. Having put:

$$\frac{Q_a}{Q_a + Q_t} = K$$

we get:

$$r = \frac{K}{g} V_0 (\eta \sqrt{2g \sqrt{\Delta h + r}} - V_0) \quad \left| \right.$$

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from which:

$$\frac{g}{K V_0} r + V_0 = \eta \sqrt{2g \sqrt{\Delta h + r}} \quad \left| \right.$$

and raising it to the quadratic:

$$\frac{g^2}{K^2 V_0^2} + \left(\frac{2g}{K} - \eta^2 2g \right) r + V_0^2 - \eta^2 2g \Delta h = 0$$

which is to say:

$$r^2 + \frac{2 K^2 V_0^2}{g} \left(\frac{1}{K} - \eta^2 \right) r + \frac{K^2 V_0^2}{g^2} (V_0^2 - \eta^2 2g \Delta h) = 0$$

from which:

$$\begin{aligned} r &= \frac{K^2 V_0^2}{g} \left\{ - \left(\frac{1}{K} - \eta^2 \right) \pm \right. \\ &\quad \left. \pm \sqrt{\left(\frac{1}{K} - \eta^2 \right)^2 - \left(\frac{1}{K^2} - \frac{\eta^2 2g \Delta h}{K^2 V_0^2} \right)} \right\} = \\ &= \frac{K^2 V_0^2}{g} \left\{ - \left(\frac{1}{K} - \eta^2 \right) \pm \right. \\ &\quad \left. \pm \sqrt{\left(\frac{1}{K} - \eta^2 \right)^2 - \frac{1}{K^2} \left(1 - \frac{\eta^2 2g \Delta h}{V_0^2} \right)} \right\} \end{aligned}$$

but $1/K < 1$; $\eta^2 < 1$ and therefore:

$$\begin{aligned} r &= \frac{K V_0^2}{g} \left\{ - (1 - K \eta^2) \pm \right. \\ &\quad \left. \pm \sqrt{(1 - K \eta^2)^2 - 1 + \frac{\eta^2 2g \Delta h}{V_0^2}} \right\} \\ (1 - K \eta^2)^2 &< 1 \quad \text{e} \quad 1 - K \eta^2 > 0 \end{aligned}$$

but:

X

If $\left((1 - K \eta^2)^2 + \eta^2 \frac{2g \Delta h}{V_0^2} \right) > 1$ is real and the selected sign is positive.

Example: let us place

$$K = \frac{1}{2} \quad V_0 = \sqrt{g} \quad \eta = 1 \quad \Delta h = 1,75$$

it will be

$$r = \frac{1}{2} \left\{ -\frac{1}{2} + \sqrt{\frac{1}{4} - 1 + 1,75} \right\} = \frac{1}{2} \left(-\frac{1}{2} + 1 \right) = 0,25$$

which is to say that about a 15% increase in the jump is obtained through the ejection effect alone.

In the case of an air current in the outlet of the diffuser of the Venturi tube, this effect leads to a much more complex calculation through other phenomena inherent in the compressible nature of the fluid. Their examination is not to be reported in this case, but they have a favorable effect, to the extent of almost doubling the pressure percentage for this jump in pressure, thus making almost equal the two power values mentioned above.

But independent of this, another intake effect which is susceptible to calculation is obtained in the type of power plant under proposal, involving the expenditures of wind energy itself which hit the static air-exhausts or exhaustion towers placed at the outlet of the diffuser, which, as such are bodies of aerodynamic resistance (suitably shaped) for providing exhaust openings at points where strong depressions are caused, as they are placed vertically over the end section of the diffuser facing upward.

On these different types of exhausts, proposed in another patent by the author³, experiments have been conducted on models

³R. Vezzani, Italian patent, "Orientation and acceleration devices for air current caught by Venturi-tube type wind-electric plants."

in a wind tunnel in comparison with centrifugal ventilators attached to air motors which, in this particular case, consisted of "Savonius" rotors with axis normal to the air current (Fig. 3).

The comparison between various exhausts is never unequivocal, because the aerodynamic effect can be compared from different points of view, as for example on the basis of an equal size of the exhaust openings, or for an equal height, or also for an equal width of the exhaust.

It is therefore only the exhaust capacity Q of the exhaust examined that is shown in the resulting curves, without calculating it with respect to other quantities. As Q increases in proportion to the wind velocity v , it is sufficient to report the value Q/v (m^2) which is independent of v . The

same exhaust capacity depends on the depression $p_a - p_1$ in the Venturi tube, and this in turn depends on the behavior of the conversion effect of the potential kinetic energy in the diffuser. But as internal pressure p_1 is practically equal to external pressure p_a , the quantities shown in Fig. 3a are those which correspond to this case. For only one exhaust, the relationship of the value of Q/v with respect to $(p_1 - p_a)/(\rho/2 - v^2)$ is shown. The other exhausts behave similarly.

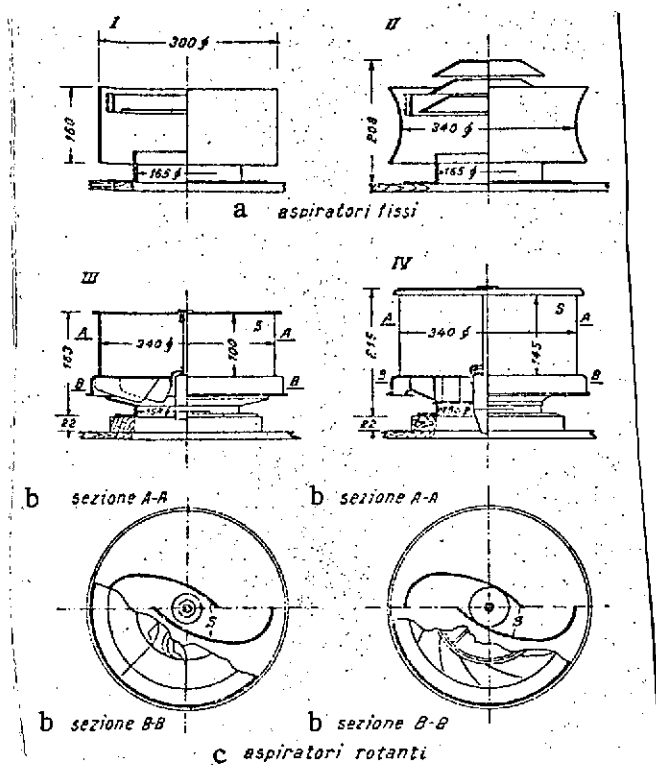


Fig. 3. Some types of fixed and rotating exhausts whose models were tested in the wind tunnel.

Key: a. Fixed exhausts
b. Section
c. Rotating exhausts

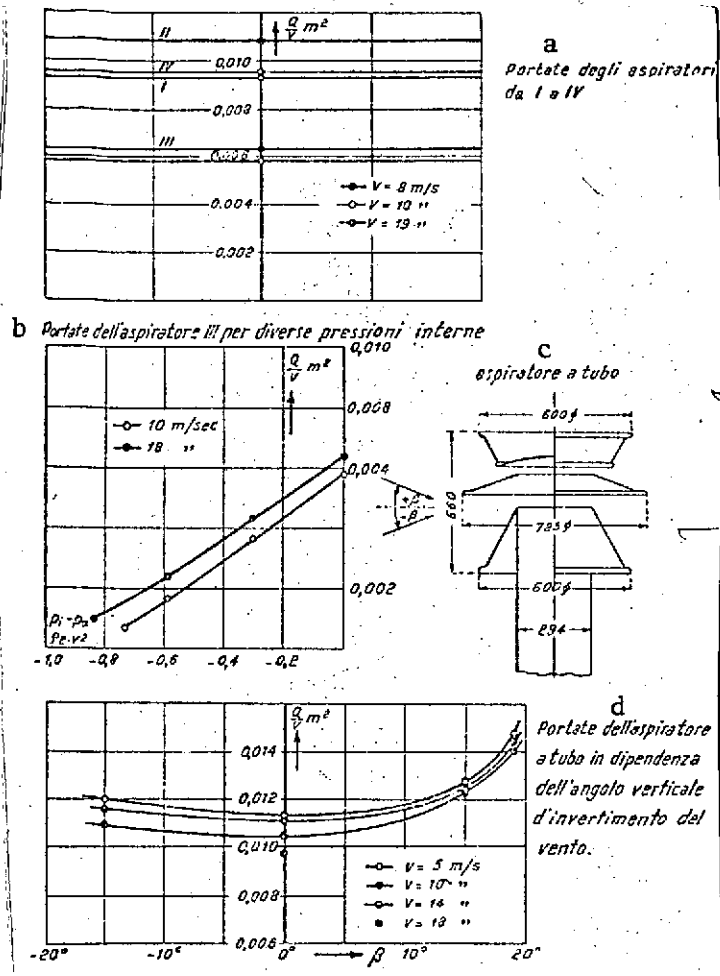


Fig. 3a. Diagrams of the capacities of the exhausts above as a function of the wind velocity, depressions, and vertical inclination of the wind as obtained in the wind tunnel.

- Key: a. Capacities of exhausts I to IV
 b. Capacities of exhaust III for different internal pressures
 c. Tube-type exhaust
 d. Capacities of tube-type exhaust dependent on vertical angle of inversion* of the wind

exhaust effect and the effective air for the exhaust, or the area hit by the wind, which is on the whole analogous to that of air

The research showed that by means of systematic procedures in this area, one can achieve notable improvements. The investigation in the wind tunnel of another type of exhaust, for example, showed that in the case of a long tube which can be hit diagonally from beneath or from above, its behavior is better with diagonal wind rather than with horizontal wind; in addition, a better effect of the velocity on the value of Q/v was verified. With respect to the preceding exhausts, one ought not to neglect the fact that this last one is considerably larger than the first ones.

From these experiments on exhaust models carried out in the wind tunnel, we also arrived at an interdependence between the

*[Translator's note: This seems to be a misprint; the correct term might be 'collision'.]

motors in general, and the "Savonius" air motor in particular. If, however, one takes into account the fact that with a suitable exhaust structure one can bring the catchment area of the air current up to the point of equalling that at the inlet of the Venturi tube, it will not seem excessive in a preliminary plan to calculate over and above an increase in available energy that is comparable to the increase which would be obtained with the device for multiplying aerodynamic pressure presented in a report by the author published in this journal [4].

Calculating with aerodynamic formulas the increase in the air current velocity on the basis of the increase in depression obtained from the wind tunnel experiments reported earlier, and subtracting from it the slowdown effect of the air motor to even a greater extent than that adopted by Prof. Teofilato in the theoretical calculation reported above, one arrives at an approximate increase in air current velocity at the inlet of 1.5 times that of natural wind. In this assertion, the only allowance made is for the experiment data obtained up to now in the wind tunnel on models of the device adopted for the plant on the island of Giglio.

The substitution of the external tube-type exhaust for the device indicated in the report cited was necessary in order to make the functioning of the whole system independent of the wind direction. Given the result of actual experiments in the wind tunnel conducted on models of the various proposed exhausts, there is no doubt that one could arrive at this substitution without drastically altering the behavior of the multiplication effect of aerodynamic pressure already shown, or of its other effects which are well known for the numerous applications that have been made of them (measurement of the velocity of aircraft, increase in the quantity of air intake of carburetors, etc.).

In both cases, allowance is made for the depression caused at the outlet opening of the Venturi tube by a supplementary device which is hit by the wind in a manner completely independent of the air motor, thereby excluding from the formation of the depression all possibilities of interference damaging to the latter, the wind tunnel experiment on which presents certain difficulties when it is associated with the Venturi tube.

Even the complete theoretical treatment of this combination has been undertaken only now by Prof. Teofilato, and for this reason, it was deemed prudent for this first preliminary plan to base the calculations of extractable power exclusively on the experiment data at hand, except at the time for building the complete model of the wind-electric plant and for experimenting with it in a wind tunnel of such diameter as to enable it also to include the provision imposed by the different directions of the prevailing winds in the selected plant location.

The results achieved with this evaluation of the energy extractable with the Venturi tube equipped with an air exhaust are a little inferior, as will be seen, to those obtained by Prof. Teofilato using the theoretical procedure reported earlier, and based only on the ejection effect produced by the wind at the outlet opening of the Venturi tube. This fact seems to show that in the first case, the deduction from the experiment data was conducted in a rather precautionary manner, thus guaranteeing in practice a production of energy which is more than sufficient for the requirement. On the other hand, as this requirement was calculated, as has been seen, in excess to enable the pyrite mine to operate at its maximum production schedule from the start, and to make allowance in case the population centers reach beforehand the demographic development anticipated for the end of a certain number of years, one may infer that the power plant and the hydraulic accumulation as planned at present, except for modifications

to be made after definitive experiments in the wind tunnel, will be able to meet the requirement for a certain number of years, during which the plant could be perfected as needed on the basis of the results achieved in the course of its operation.

In addition, it would not seem excessively optimistic to consider the theoretical efficiency η of the intubated air motor as reaching 80% in normal work load conditions, and perhaps even more, as it appears in the following table calculated by Prof. E. Pistolesi for an air motor fan blade intubated in a Venturi ("The problem of the intubated airscrew," School of Engineering, Pisa, 1924).

$y = 0,05$	$y = 0,10$	$y = 0,15$
$\eta = 0,172$	$\eta = 0,538$	$\eta = 0,681$
$y = 0,20$	$y = 0,25$	$y = 0,30$
$\eta = 0,756$	$\eta = 0,801$	$\eta = 0,831$
$y = 0,40$	$y = 0,45$	$y = 0,50$
$\eta = 0,852$	$\eta = 0,868$	$\eta = 0,888$

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where y is the efficiency ratio V_0/nD .

For converting what is shown above into figures, there is only the exhaust effect at the forward mouth of the Venturi tube acquired through the depression in the neck caused by placing at the outlet of the Venturi the static devices described earlier. The air current velocity will increase by 1.5 times, and therefore the usable power will increase by $(1.5)^3 = 3.37$ times.

With this established, going from theoretical maximum power to the effective power, an efficiency of 65% is already being used for an air motor in free air to take into account losses in the gear system. In such a case, this is justified by losses due to friction and change of air current direction. The theoretical

efficiency of an air motor exposed to free air is, as has been seen, about $16/27 = 0.60$, while that of an intubated air motor is 0.80, on the average. There will therefore be an efficiency increase of about 33%. In conclusion, the increase in power of an air motor intubated in the Venturi will be $3.37 \times 1.33 = 4.48$.

Extracting the quadratic radical from this multiplication factor, it follows that for obtaining the same power as an air motor exposed to free air, it will suffice to make the diameter of the forward mouth of the Venturi 2.12 times smaller, which is to say $86/2.12 = 40$ m.

In conclusion, if this is done in such a way (as will be seen later) as to maintain its number of revolutions in constant ratio to the wind velocity and equal to the optimal value of about 4.5, by varying the angle of incidence of the air motor blades, and if the diffusor of the Venturi tube and the exhaust apparatus at its outlet are adjusted properly, it would be possible to reduce by half the diameter of the catchment area of the air current, and therefore to bring it to about 40 m for the requirement anticipated for the island of Giglio; that is to say, a little smaller than that calculated theoretically by Prof. Teofilato to allow for only the ejection effect produced by the wind at the outlet of the Venturi tube.

Calculation of the Air Motor

The diameter of the Venturi tube at the neck is fixed at 10 m, and, because of what was learned in the theoretical calculations on the air motor and in deductions made from the experiments conducted in the wind tunnel on models for a maximum permissible wind velocity of 20 m/sec, over which figure the safety of the machinery would have been compromised, V will be 44 m/sec, and the maximum theoretical power, as the airscrew is intubated, will

be -- in terms of efficiency, as we have said -- a little less than the average value of 0.80, i.e. 0.75:

$$P_{\max} = 1.25 \cdot 0.000285 V^3 D^2 = 3035 \text{ kW}$$

To move from this theoretical power output to the effective output produced by the generator, we will apply the coefficient 0.65 already adopted for air motors exposed to free air (although it is possible in this case, as will be seen, to mount the generator directly on the same shaft as the air motor), obtaining about 2000 kW installed power output.

For the number of revolutions corresponding to the above-mentioned velocity, with the behavior coefficient of the velocities -- i.e. the relationship between the peripheral velocity of the blades and the velocity of the wind -- placed at 4.5, or equal to the optimum value, we will get:

$$U_{\text{periph}} = 4.5 \cdot 44 \text{ m/sec} = 198 \text{ m/sec}$$

and the number of revolutions will be

$$N = \frac{60 \cdot 198}{D} = 378 \text{ rpm}$$

For the average wind velocity of 7 m/sec, the figure would be 132 rpm. These values are to be kept in mind for the study of the electricity generator.

At this point, one will observe that the functioning of an intubated air motor can be assimilated completely into that of a Kaplan turbine or a diffuser type airscrew, except for the compressible property of the fluid which, however, as can be easily demonstrated for an air velocity much lower than that of sound, does not have any practical influence on the final results.

Starting with a multidimensional bearing on the problem, one can conduct the study of the blades in a manner analogous

to that of airplane wings. Since the theory of aerodynamics supplies the elements necessary for the calculation of the best angle of incidence of a wing for achieving the maximum sustentation in its motion, it thus allows one to proceed to the design of blades of an air motor for obtaining maximum efficiency. It is also possible to evaluate the complex effects inherent in the number of blades, the values of the angles of incidence of the blades for inflow and outflow, the multidimensionality of the current, as well as in the real aspect and aerodynamic conformation along the length of the blades. By thus taking into account all the circumstances that influence the power output of the air motor, one can arrive at a calculation procedure sufficiently precise to allow the realization of a level of approximation higher than that of other known methods.

Concerning the efficiency attainable with an intubated air motor of this type, we have already referred to the notable improvement it represents in comparison to that of an air motor exposed to free air. Everything that has since been introduced into the Kaplan turbines or into airscrews for improving their efficiency could be transferred to this type of air motor, in which the change in the fluid property does not bring, as has been seen, consequences that are essential to the calculation of the blades and in its functioning.

In addition, its reduced dimensions in comparison to the necessarily enormous dimensions of air motors exposed to free air make it easier to calculate the required resistance to mechanical and dynamic effects introduced by the wind and by centrifugal force; while vibrations caused by the periodicity of the gusts, which have a great negative influence on the safety of the air motor, and especially because of the resonance phenomenon if the oscillation period of the giant blades should just coincide with or be just about equal to that of the

vibrations themselves, are practically eliminated; This is also due to the fact that the air motor is intubated and has small dimensions, as well as to the attenuation of the gustiness of the wind achieved by means of the equalizing effect of the static exhaust devices at the outlet of the diffusor which, in this respect, function as stabilizers.

Lastly, the construction of the air motor is greatly facilitated both by the material, solid steel, with which it can be made, and by the feasibility of fusion in the form of precisely calculated profiles and of the subsequent milling with machine tools already being used in normal factory work.

Furthermore, for the regulation of the motive element in a wind electric plant of this type according to the wind velocity and load variation, everything that has been studied and adopted for the Kaplan turbine or airscrews can be transferred to the intubated air motor, except for the substitution of hydraulic controls with anemographic signalers of wind gusts of the /408 Pitot type, or of the special type patented by the author⁴, involving a rotating measuring device and an electric recorder.

It will, however, be necessary to return -- after the question of the electrical generator has been treated -- to the important discussion of determining in what conditions and in what manner the regulation of the extremely variable wind energy could take place as it changes the load in this wind-electric plant. On the one hand, the plant adopts new methods for the attenuation of crests in wind velocity, and for the electric transmission of commands and control maneuvers, and on the other hand, relies on a high degree of automation for the introduction and exclusion of the intermediary pumping action in the utilization of the

⁴R. Vezzani, Italian patent, "New three-dimensional accelerometric electric anemograph for measuring the instantaneous velocity of wind and direction in space.

produced output, for the purpose of improving the efficiency to the maximum.

The position of the air motor will not be exactly in the neck section of the Venturi tube, but rather at about one-third of its diameter, i.e., at 3.33 m toward downstream. In this way, the best exploitation will be achieved for the contracted air vein which, as is known, moves away from the tube wall until it reaches its greatest contraction precisely at about that distance from the neck, simultaneously with the distancing of the tips of the air motor blades from the tube wall in the manner of assuring a better functioning efficiency. In addition, this shift downstream will allow an increase in the neck diameter, maintaining the shift for an air motor of 10 m at about 1.80 m, which will decrease the divergence of the tube toward downstream, or the diffuser, by about 1° , while the convergence of the forward tract of the tube will approach the 30° optimum value (about 35°).

Exactly below it, on the vertical part of the air motor shaft, is installed the main generator of the set, which is of the direct-current type and follows the Ward-Leonard system, which will be adopted (as will be seen later) for the production of direct-current electrical energy via the pumps, or directly in alternating current with constant voltage and frequency.

The regulating system with automatic controls will be located, together with the groups of generators, in a small control center excavated in the rock beneath the neck of the Venturi tube, and which one will be able to enter through a convenient stairway from a suitable window, opened for the excavation of the narrowest part of the Venturi tube that will have to be constructed underground.

In this way the length of the shaft hole of the air motor generator system will not exceed 20 m, while the most delicate part of the machinery and the electric and hydraulic controls for the regulation of the air motor blades will be protected from bad weather and will permit easy entry for surveillance and possible repairs. Above the intake mouths on top of a small iron frame will be installed an anemograph which controls the regulation of the air motor and the generator set in a manner which will be shown later.

Description of the Other Parts of the Plant

The complex of apparatus indispensable for achieving the aforementioned purposes of water accumulation and energy production is constituted as follows (Fig. 4):

- 1) wind motor connected to a direct-current generator set of constant voltage of about 2000 V even for variable velocities;
- 2) power line for the transmission of energy from the generator set to the pumping station;
- 3) motor-pump system of a single unit or composed of several units flowing out into a single pressure conduit, which in turn is connected both to the turbine for driving the alternator, and to the pipe for conduction into the reservoir;
- 4) alternator of the required power capacity (2000 kW installed) which in turn is driven by:
- 5) turbine fed by the pressure conduit from the pumps which then continue to the accumulation basin.

We will also add to these a rotating converter unit of continuous alternating current for the periods in which the wind energy equals the required energy, thus avoiding the numerous energy losses which intervene when the hydraulic system has to function.

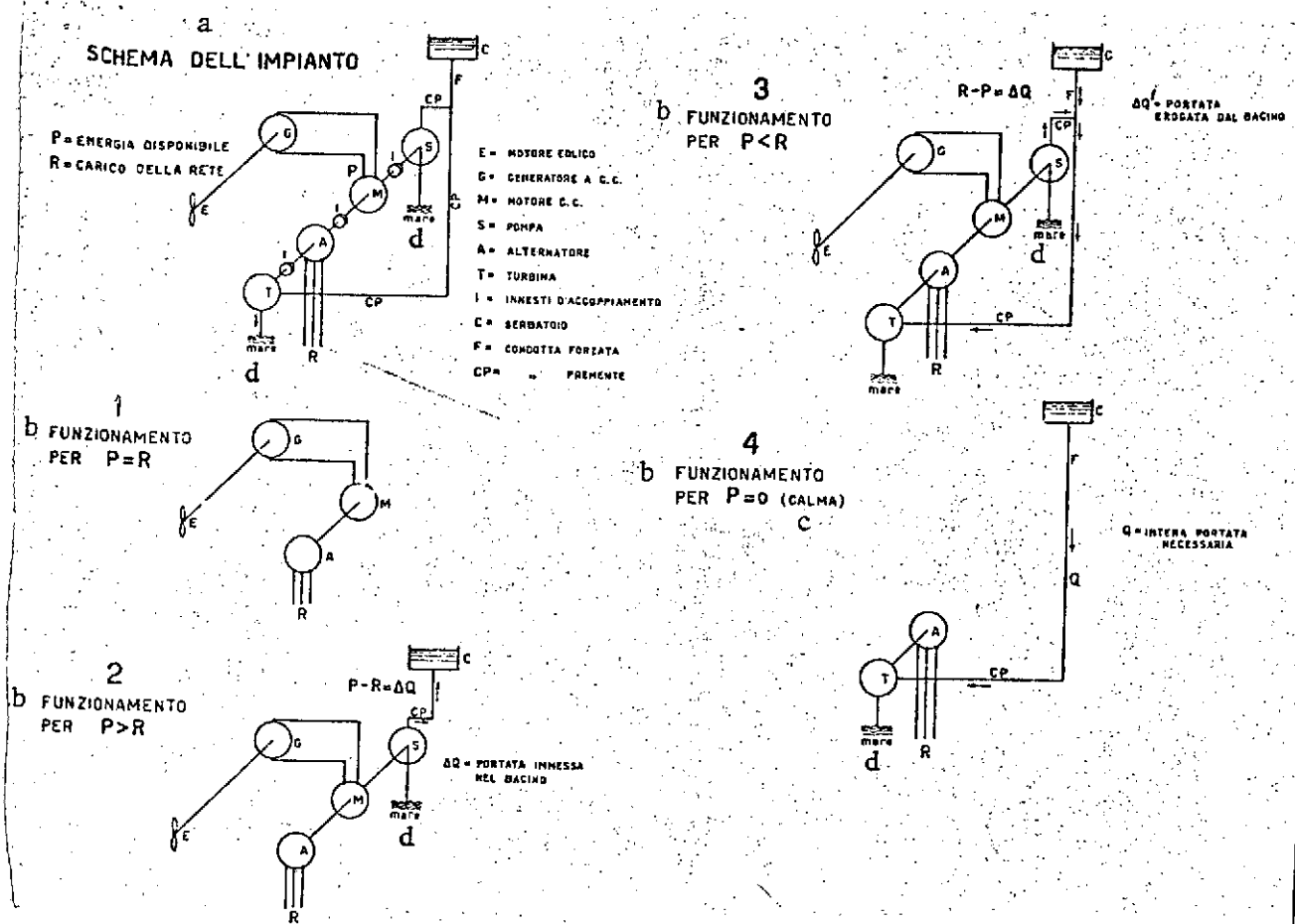


Fig. 4. Scheme of the plant and the various possible functioning conditions.

- | | |
|------------------------------|--|
| Key: a. Scheme of the plant | T = Turbine |
| b. Function for | I = Connection clutches |
| c. Calm | C = Reservoir |
| d. Sea | F = Full pipe |
| P = Available energy | CP = Pressure pipe |
| R = Network load | ΔQ = Capacity carried into basin |
| E = Wind motor | $\Delta Q'$ = Capacity supplied from basin |
| G = Direct current generator | Q = Entire capacity necessary |
| M = Direct current motor | |
| S = Pump | |
| A = Alternator | |

Apart from this, one needs to consider different conditions of operation;

- a) the wind energy exceeds the required energy. The pump system will operate together with the turbo-alternator system, thus accumulating water in the basin;
- b) the wind energy is lower than the required energy. The pumping will still take place at a reduced capacity and the alternator will function at the required load, while the turbine will be fed partly by the pump and partly by the water in the basin;
- c) calm or complete inactivity of the wind. Only the turbo-alternator unit will function as an ordinary hydroelectric plant, and only on the water accumulated in the reservoir.

Description of the Wind Catchment Apparatus

As seen in the design (Figs. 4a and 5b), a horizontal platform, of a circular ground-plan 54 m in diameter will be constructed on the Pagana hill with dry wall. The masonry necessary for this structure will be extracted from the excavation which must be carried out for the diffusor.

On this platform the intake mouths will be constructed, covering the whole horizon, subdivided into octants of 45° each. The construction of the complex, which is expected to be in thin-structured reinforced concrete, similar to that of large hangars, will be completely stable, even with the considerable dimensions required. The shape of these giant vaults will be approximately elliptical, with upright sides 16 m high, and 20 m wide at the impost of the parabola. These mouths, each of an area equal to half of what was anticipated, converge toward the center, stopping 12 m from it. In the interior, will be a half-dome, rotatable by control, which carries the air to the air motor through successive connections, installed with vertical axis in the neck 10 m

in diameter at the beginning of the diffuser which, after a short vertical tract, will turn gradually toward the outlet mouth.

Control of the half-dome will be conducted by means of an anemograph, which, with suitable electric controls, will turn the mouth of the half-dome in such a way as to set it in the direction of the incoming air column at the external mouths, going from one octant to another and collecting the air which enters from two adjacent mouths.

In the initial years of operation, not all of the energy produced will be distributed, and for this reason, rather than providing intake mouths on the whole horizontal circle, it will be possible in the meantime to construct only those of the two quadrants that are struck most by the winds, and which happen to be contained between the azimuths of $337^{\circ}30'$ and $67^{\circ}30'$ (approximately NE) and between $202^{\circ}30'$ and $293^{\circ}20'$ (approximately SW). In limiting the mouths to these quadrants, one would lose less than 30%. Then, when the energy requirement increases, the intake mouths could also be constructed for the remaining quadrants. In the present plan, however, the mouths on the whole horizontal circle have been specified.

Study of the Diffuser, the Outlet Mouth and the Reservoir Capacity

The Venturi tube air motor system (Figs. 5, 5a and 5b) is mainly based on the efficiency of the diffuser, which is to say the transformation of the potential kinetic energy into flow expansion. The experiments conducted on models with liquids rather than with compressible gases which, other than for velocities far from that of sound, behave similarly, demonstrated that expansions with small divergences favor the formation of a depression better than those with larger divergences. The optimal value occurs at 8° .

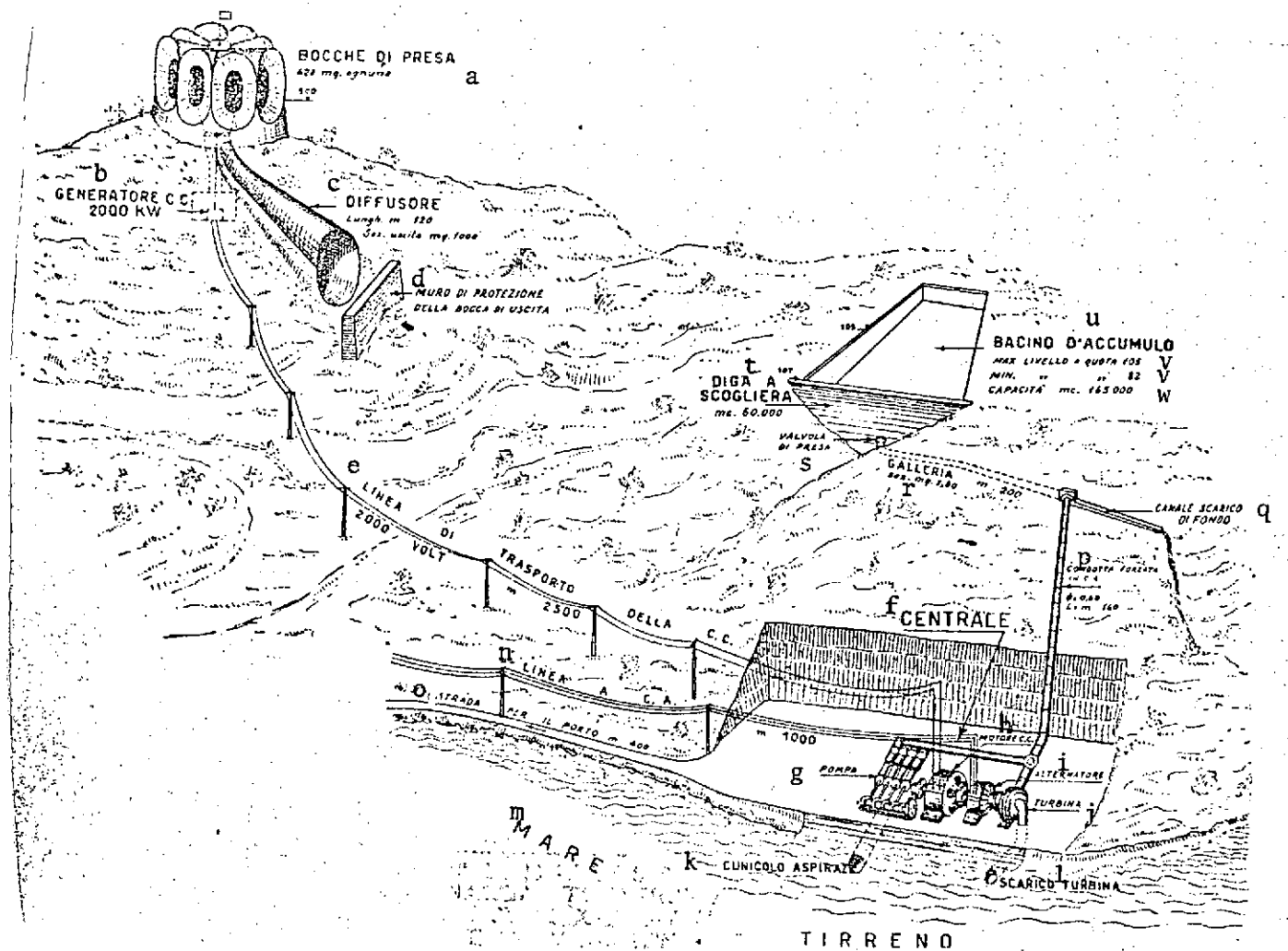


Fig. 4a. Schematic view of the whole complex of the wind-hydroelectric power plant, without indication of the exhaust at the outlet mouth of the diffusor (still under study).

- Key: a. Intake mouths, 628 m² each
 b. Continuous current generator
 c. Diffusor: length 120 m; outlet section 1000 m²
 d. Wall for protection of outlet mouth
 e. Continuous current transmission line
 f. Power station
 g. Pump
 h. Continuous current motor
 i. Alternator
 j. Turbine
 k. Underwater intake
 l. Turbine discharge

[Key continued on following page.]

Key to Fig. 4a, continued:

- m. Tyrrhenian sea
- n. Alternating current power line
- o. Road to harbor
- p. Full pipe (ascending)
- q. Discharge channel
- r. Water tunnel section
- s. Intake valve
- t. Rock-fill dike
- u. Accumulation basin
- v. Level elevation
- w. Capacity

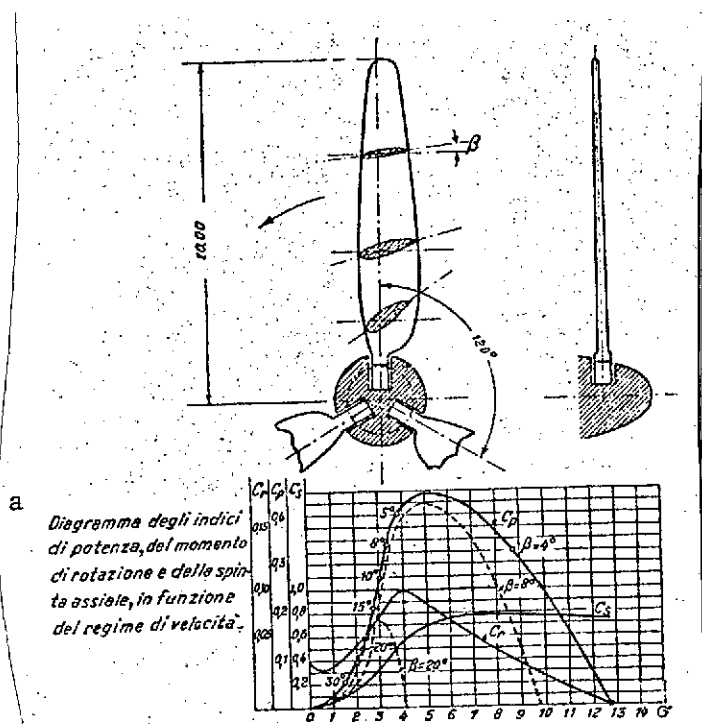


Fig. 5. Model of the air motor with blades revolvable on own axis and diagrams obtained in the wind tunnel for coefficients C_p , C_r and C_s as a function of u/v .

Key: a. Diagram of the power output indices, of the moment of rotation and of the axial thrust as a function of velocity behavior.

On the other hand, with small divergences, the length of the diffusor becomes considerable, because the outlet mouth becomes as wide as that of the inlet, and this causes a loss due to friction of the same magnitude as that produced by a large divergence. For this reason, a divergence of 12° was adopted. If we fix /411 the diameter of the air motor at 10 m and that of the outlet at 35 m, the length of the diffusor will be:

$$\frac{17,5 - 5}{\tan 6^\circ} = \frac{12,5}{0,105} = 119 \text{ m.}$$

This could extend along the slope in the direction of WNW, which is least exposed, and can be half-encased by the terrain.

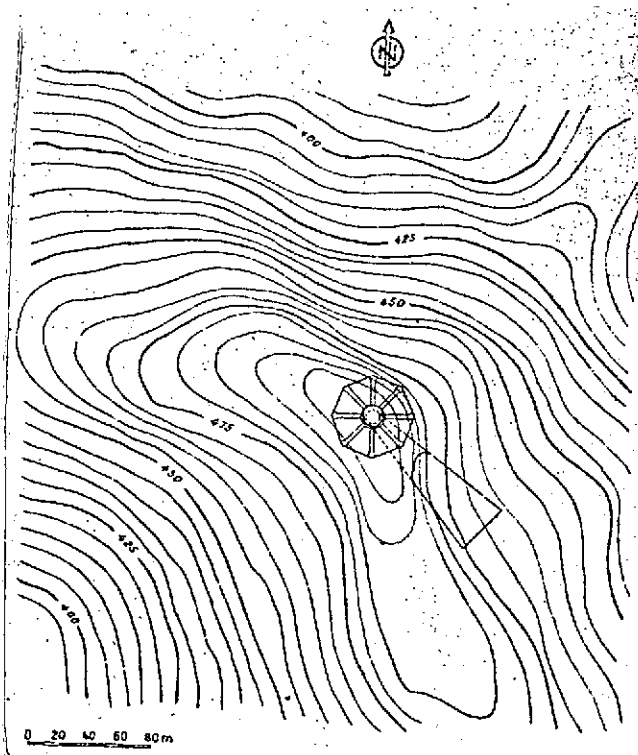


Fig. 5a. Location of the plant (Poggio della Pagana hill), with indication of the wind-electric plant's orientation.

Provided that the area of the sections from the neck of the Venturi to the outlet mouth continues to increase in proper relation to the calculated divergence, one may adopt for their shape something more suitable, whether from the practical standpoint of construction, or from the economic standpoint.

While the diffusor can be designed with circular sections, the executive office will determine what the most suitable solution will be.

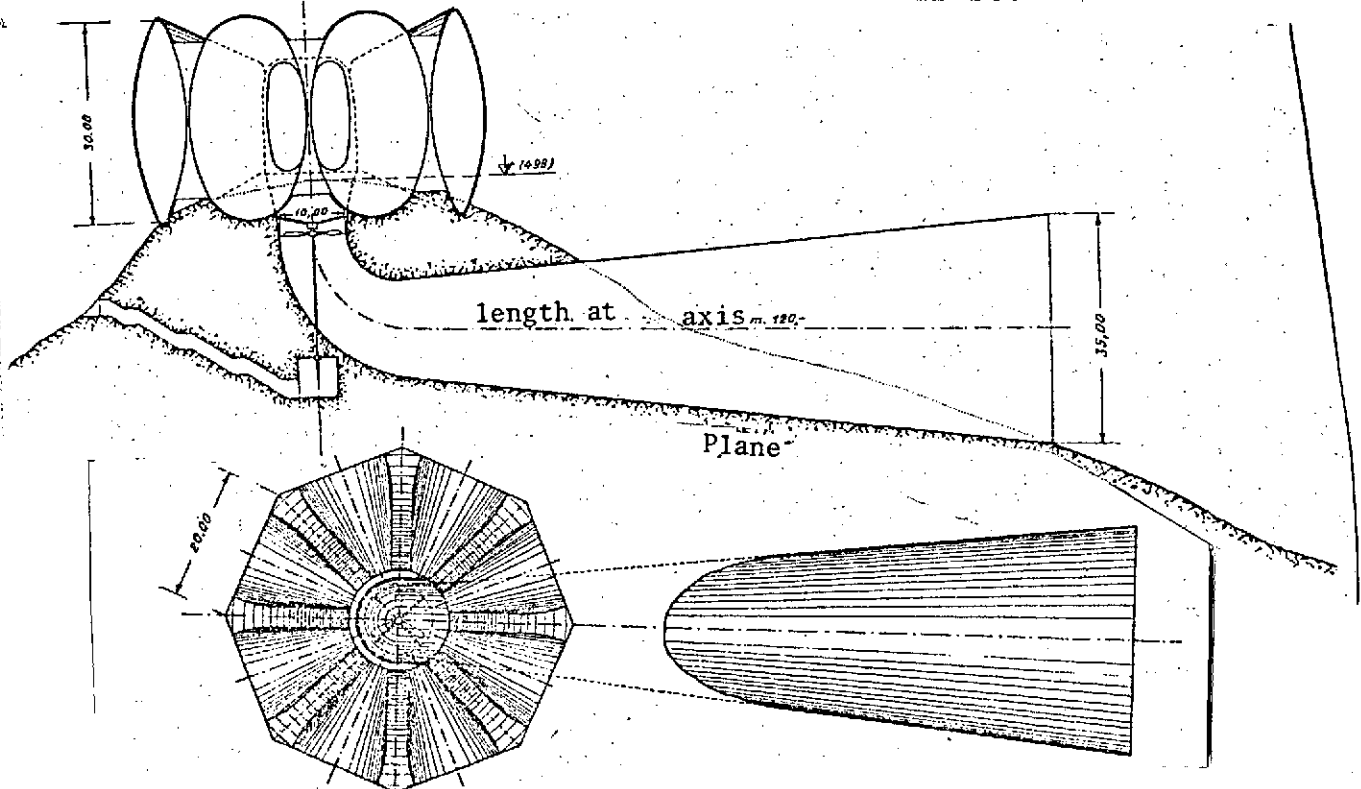


Fig. 5b. Elevation and plane of the wind-electric plant. The fixed exhaust at the diffusor outlet, still under study, has been omitted.

At the extremity of the diffuser, the installation is prescribed for static exhaust devices, to which we have referred earlier, but which are not shown in Fig. 5b; we are waiting for the outcome of further studies and tests in the tunnel, which are currently in progress, in order to establish the definite form of realization.

On the basis of the diameter of the intake mouth, fixed, as has been stated, at 40 m, the effective power outputs developed respectively for each velocity stage were calculated as follows:

$V = 0-2$ m/sec	$P_e = 0,795$ kW
$V = 2-4$ m/sec	$P_e = 9,6$ kW
$V = 4-6$ m/sec	$P_e = 42,8$ kW
$V = 6-8$ m/sec	$P_e = 120$ kW
$V = 8-10$ m/sec	$P_e = 234$ kW
$V = 10-12$ m/sec	$P_e = 428$ kW
$V = 12-14$ m/sec	$P_e = 700$ kW
$V = 14-16$ m/sec	$P_e = 1090$ kW
$V = 16-18$ m/sec	$P_e = 1600$ kW
$V = 18-20$ m/sec	$P_e = 2000$ kW

Applying to each power output the duration in each month of the year of the respective wind velocities according to the duration curves traced in the diagrams shown as examples (Figs. 6, 6a, 6b and 6c), we obtain the monthly produceable energy, on the basis of which were traced the curves of the available energies and the diagram of requirement and energy production for each month (Fig. 6d). From this last diagram, it is easy to verify that during the summer season there are deficiencies in energy production with respect to the requirement, and in particular in the months of July and August. Adding together these deficiencies, we would get for the months of June-September altogether an energy shortage of about 180,000 kWh, which corresponds to the requirement for 30 days calculated, as we have stated, on the basis of 300 kW for 16 hours and 200 kW for 8 hours. But in this period, there are exactly 16 Sundays, on which the 16-hour

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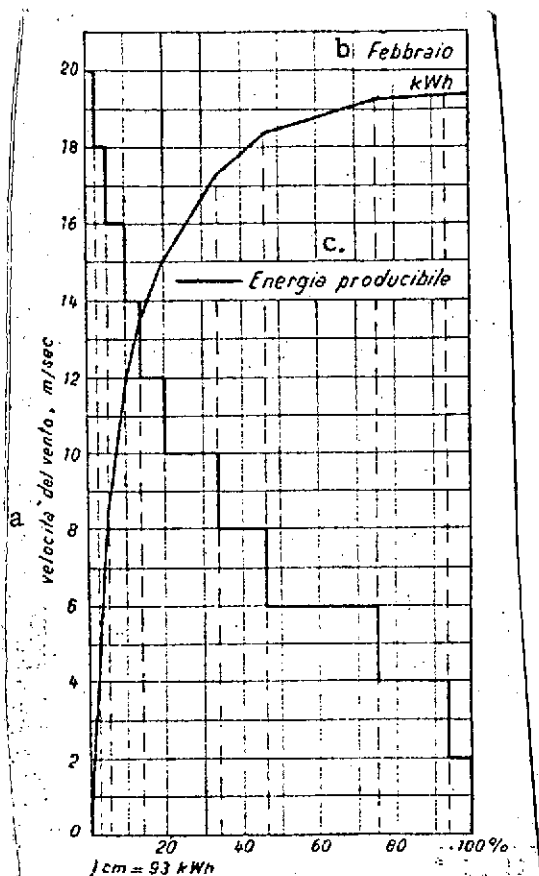


Fig. 6. Curve of the duration of wind velocities and diagram of the produceable energy in February.

Key: a. Wind velocity
b. February
c. Produceable energy

work shift does not take place, to the measure of the equivalent of $16 \cdot 3/5 = 10$ work days less, and thus, in reality, the energy deficiency will correspond to only 20 work days, which is to say 128,000 kWh.

The energy necessary for passing the summer period should be thus accumulated in a reservoir of a capacity given by the formula $E_s = \frac{C \cdot \Sigma h m}{500}$ in which, putting $\Sigma h m = 70$ m as the average of the useful falls, we obtain $128,000 = \frac{C \cdot 70}{500}$, from which is obtained $C = 914,285 \text{ m}^3$.

From the surveys conducted on the island and from geological research completed by experts, there emerged, however, just one valley in proximity to the sea which lent itself to the formation, by means of damming with a moderate dike (about 20 m high) a reservoir with the above-mentioned capacity, and with such an average fall of accumulated water; this was the valley of Ortana, opening into the bay of Allume on the western coast, which presented unfavorable geological characteristics. In fact, from accurate geological maps of the island and on-site investigations, it became apparent that though this point passed the demarcation line between the granite formations and those of limestone which constitute the subsoil of the island, and thus the stability of the foundations and supports of the dam could be compromised by

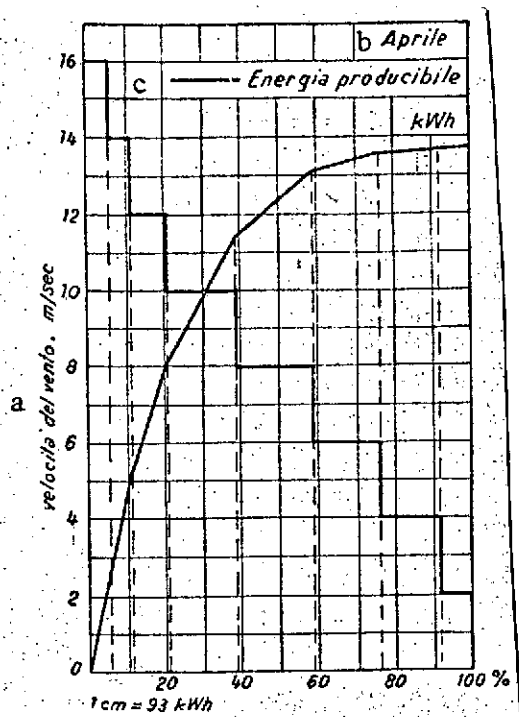


Fig. 6a. Curve of the duration of wind velocities and diagram of the produceable energy in April.

Key: a. Wind velocity
b. April
c. Produceable energy

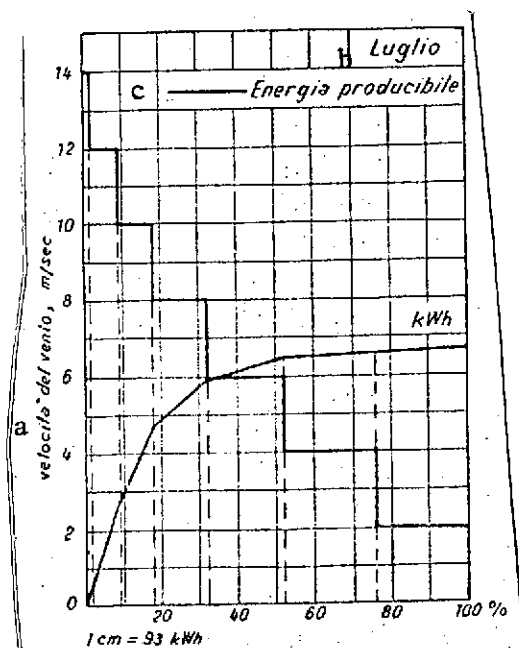


Fig. 6b. Curve of the duration of wind velocities and diagram of the produceable energy in July.

Key: a. Wind velocity
b. July
c. Produceable energy

this disparity in the geological property of the terrains. In addition, the zone of broken limestone is located just above the aforementioned pyrite mine, and for this reason, the objection that the infiltration of the water accumulated above would damage the excavation works and the galleries of the mine would be legitimate and not easily contestable.

Though allowing for ample reservation for subsequent studies on the feasibility of making the water accumulation basin perfectly safe from infiltration by means of liquid cement or "gunite" injections and consolidating the foundations and supports of the dam by the same method, we have, for now, in the preliminary planning office, abandoned the proposed solution, which nevertheless had offered the most convenient construction, whether due to the flat shape of the valley to be dammed, or to the immediate vicinity of the sea.

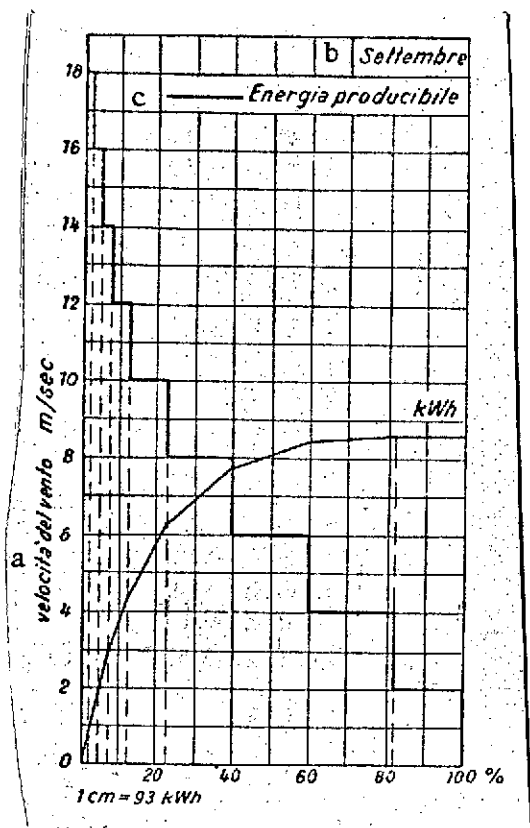


Fig. 6c. Curve of the duration of wind velocities and diagram of the produceable energy in the month of September.

Key: a. Wind velocity
b. September
c. Produceable energy

Turning then to a compromise solution, we therefore had to resort to the choice of a small valley in front of the inhabited center of Giglio-Porto harbor, which can, however, accommodate, through damming with a dike, a reservoir of limited capacity and an average fall corresponding to hardly one third of the required hydroelectric energy. This could be reduced by hundreds of thousands of kWh by taking into account the already-mentioned possibility of excluding the intermediary direct current cycle and the related pumps, thus directly producing the energy in alternating current of constant voltage

and frequency for feeding immediately into the distribution network, or of driving, under continuous current and constant voltage, a converter for the production of three-phase energy.

In this last case, the efficiency of the whole plant improves notably, due to the exclusion of the pumps, while in the first case, with the elimination of the converter, the efficiency is even greater.

The remaining energy deficiency in the summer period, calculated (after what has been mentioned) to be 60,000 kWh,

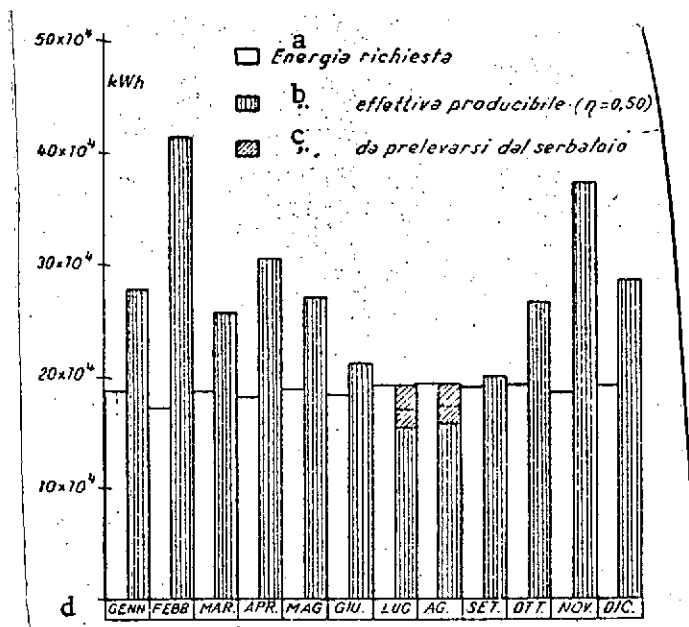


Fig. 6d. Diagram of the requirement and energy production for each month.

Key: a. Required energy
 b. Effective produceable energy
 c. Energy to be drawn from the reservoir
 d. [Months: Jan, Feb, etc.]

could not be overcome without relying on the existing thermoelectric plant near the pyrite mine, which reaches a power output of 500 kW. It would therefore increase the average production cost of the 3 million kWh needed through thermic production of the extra 60,000 kWh, assuming that for each kWh, it would consume 1/2 kg fuel oil, whose cost on the island is 100 lire/kg. Undoubtedly, this cost increase, not strictly due to the wind-electric plant,

would lead to mistaken conclusions about the economic suitability of the plant itself.

In order to avoid this inconvenience, we have provided, still keeping the project for a power plant with hydraulic accumulation by pumping, for the study of other possible solutions of the problem, which is to say the accumulation of excess wind energy in the form of air compressed into cylinders and its utilization in a gas turbine, or in the form of steam compressed in accumulators using steam produced by heating the water in an electric boiler with heat produced electrically in the air motor, and finally, in the form of hydrogen compressed into high-pressure cylinders, obtained by the electrolysis of the water produced by

wind energy. Of these three different forms of energy accumulation, research is now taking place on which would be the most economic, and also the simplest for bringing to the support of the hydroelectric plant in the summer period, or whatever period of calm or weak winds.

Accumulation Basin for the Pumped Water

Returning now to the above-mentioned reduced solution for this first plant, which is already of considerable power, the production will have to reach, as has been stated, 300 kW for 16 hours during the day plus 200 kW for 8 hours, and it will still require a plant capable of supplying the requirement of 6400 kWh/day.

In desiring to have a reserve capable of supplying the requirement for possibly 5 consecutive days of absolute calm, an occurrence not yet observed, we will have to make available an accumulation of 32,000 effective kWh. Naturally, having considered the variability of the wind energy and the efficiency of the whole system which could come to about 0.40, we must count on the wind motor for a maximum power output that is greater than what is necessary; an output we have fixed at 2000 kW.

Allowing for a production of 450 effective kW, we should have, with an average head of 95 m, for the production of hydroelectric energy $450 \times 7.5 \times p \times 95$, assuming an efficiency of about 0.76, from which the necessary capacity p will be

$$\frac{450}{7.5 \times 95} = 0.632 \text{ m}^3/\text{sec}$$

For the reserve, we should have a capacity for producing 32,000 kWh, as has already been seen; for the 16 hours of work during the day, we will have an average power output of $6400/16 = 400$ kW for which, with the head of 95 m, would be required an

approximate average capacity of $400 / (7.5 \times 95) = 0.561 \text{ m}^3/\text{sec}$ for the 16 hours, which is to say $32,000 \text{ m}^3/\text{day}$, and 5 days of continuous absolute calm would require $160,000 \text{ m}^3$.

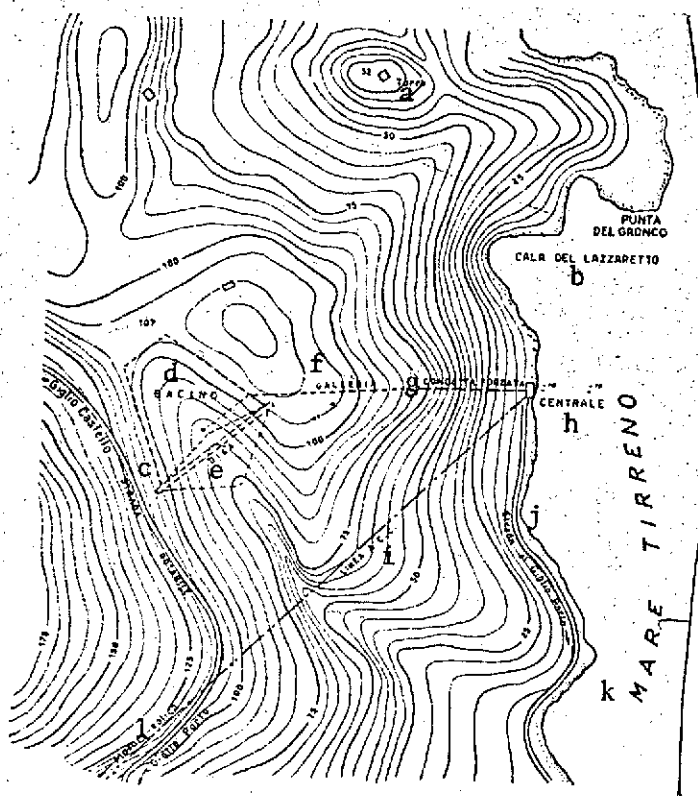


Fig. 7. Topography of the hydraulic accumulation basin, full pipe conduit and power station in the first solution proposed (small valley over the bay of Lazzaretto).

Key: a. Tower
 b. Bay of Lazzaretto
 c. Passable road
 d. Basin
 e. Dike
 f. Water tunnel
 g. Full pipe conduit
 h. Power station
 i. Direct current power line
 j. Road to Giglio Porto harbor
 k. Tyrrhenian sea
 l. Wind motor

The construction of the basin could be achieved either by damming one of the numerous small valleys, or by obtaining it by means of excavating a cistern of adequate capacity. Numerous investigations were made on-site to seek out a valley over which the basin can be placed but, generally speaking, the valley bottoms were very steep, and a dike of considerable height would have been necessary for attaining the required capacity. We thus went to a solution which utilizes both of the methods for creating the necessary capacity. A small valley (Fig. 7) particularly suited for its favorable location is the one which is situated on the bay of Lazzaretto near the Giglio harbor, and by excavating its upper part, the objective will be achieved. In

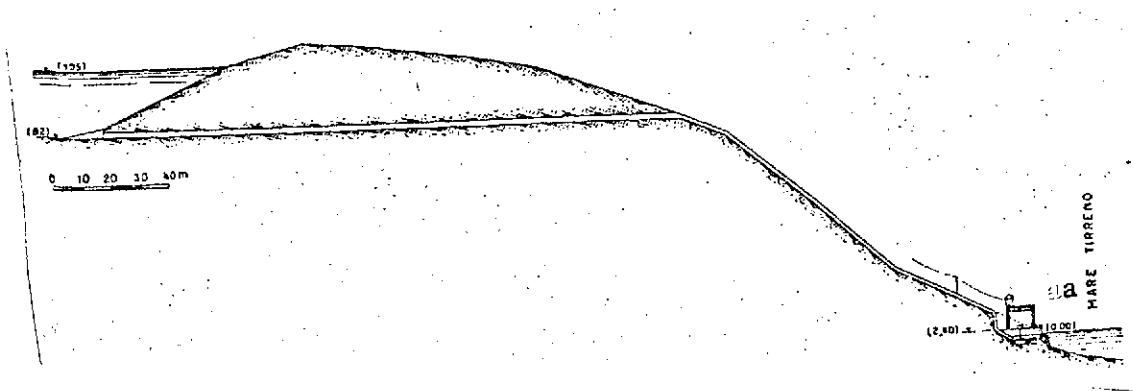


Fig. 8. Full pipe conduit in the first solution (bay of Lazzaretto).

Key: a. Tyrrhenian Sea

fact, with a dike of only 25 m in height, one can reach a capacity even greater than $160,000 \text{ m}^3$. Adapting the rock-fill method for the dike, it would be possible to excavate the rocks needed from the valley bottom at its upper part. With this system, the work cost could be reduced to the minimum, because it would be possible to carry the rocks to the work site directly from the excavation site next to the dike, by means of ordinary construction equipment. This will thus create a basin (Fig. 8b) with a water surface of 9850 m^2 , walls with $1/5$ inclination, a bottom gradient of 5% and a $165,000 \text{ m}^3$ capacity. The volume of the dike, including the crown, comes to about $60,000 \text{ m}^3$. The necessary excavation, mainly superficial, will be about $87,000 \text{ m}^3$ including the upper stratum which must be removed and some soil and gravel accumulated by time. The dike (Fig. 8a), designed according to the R.D. [expansion unknown] of October 1, 1931, No. 1370, and regulated accordingly, will have an up-hill facing with an inclination at the base of 0.5 to one of height and one of thickness at every point -- equal to double the height.

The dike will be raised step by step through manually adjusted layers, with a bearing almost normal to the contour lines. The maximum unit load at the bottom will be 4.5 kg/cm^2 . On the up-hill

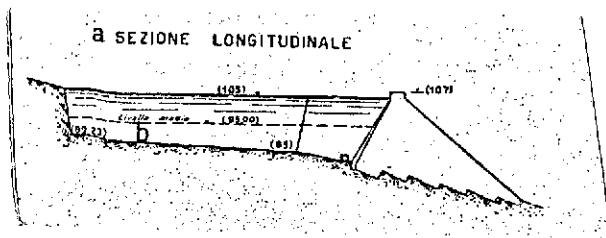


Fig. 8a. Rock-fill dike in the first solution.

Key: a. Longitudinal section
b. Median level

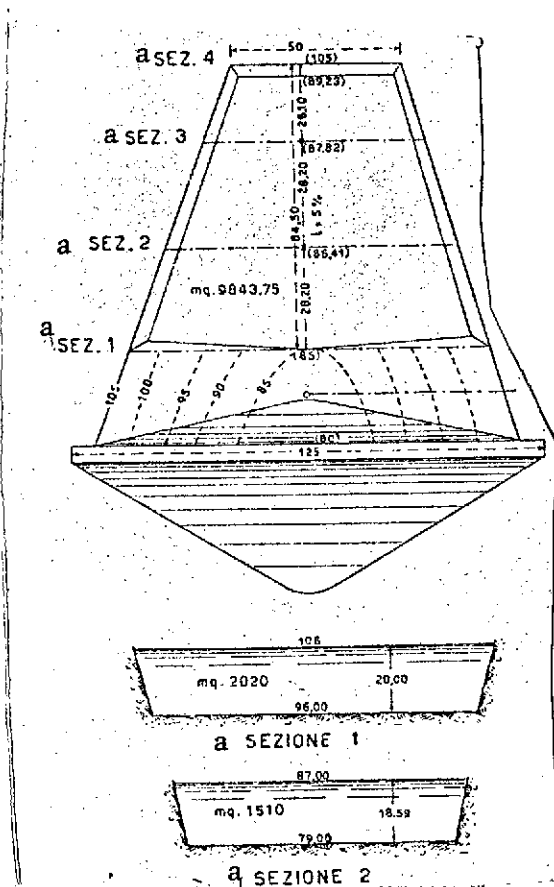


Fig. 8b. Hydraulic accumulation basin in plane and section in the first solution.

Key: a. Section

facing, an impermeable diaphragm will be used in reinforced concrete, with suitable expansion joints, and embedded at the base in a groove of adequate depth. Cement injections are not believed to be necessary as the granite rock is absolutely impermeable. Only if fractures or breaks in continuity are encountered ⁴¹⁴ would we use bentonite, wherever required.

The diaphragm thickness will be 0.050 m on the average. There will be no need for a spillway or overflow discharges as the reservoir is supplied only by a pump. The location selected is near the passable road from Porto al Castello harbor and is therefore very favorable for the access of materials and personnel.

Full Pipe Conduit, the Pumping Station and Production of Three-Phase Energy

The full pipe conduit (Fig. 8) begins at the elevation of 82 m, and its first tract, about 230 m long due to its

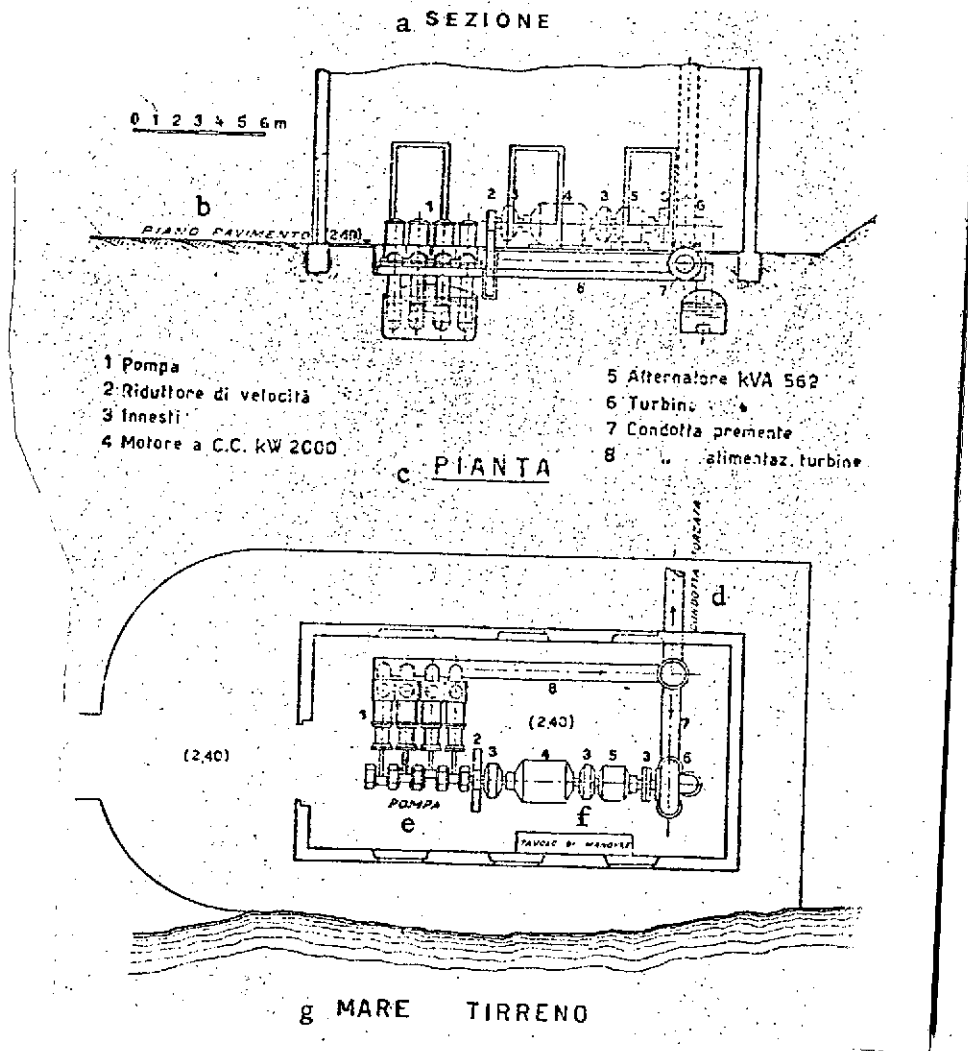


Fig. 8c. Station for the hydraulic accumulation pumps, and for the turbine and alternator for energy production.

- | | | | |
|---------|-------------------|---|--------------------------|
| Key: a. | Section | 1 | Pump |
| b. | Ground level | 2 | Velocity reducer |
| c. | Plane | 3 | Clutches |
| d. | Full pipe conduit | 4 | Direct current motor |
| e. | Pump | 5 | Alternator |
| f. | Control panel | 6 | Turbine |
| g. | Tyrrhenian Sea | 7 | Pressure pipe |
| | | 8 | Pipe for feeding turbine |

extension beyond the body of the dike, will emerge at the bottom in a small tunnel of the smallest possible section. Out of the opening, it will veer toward the center with an exactly west-east bearing which, by cutting the horizontal curve normally, presents the shortest distance. If the exit tunnel were to present a perfect fit, it could only be used by itself as full pipe conduit, as the maximum load is only 25 m.

At the tunnel outlet, the pipe will have a small shunt, equipped with a sluice-gate, for enabling the basin to be emptied.

The power station (Fig. 8c) will be built over a small square, to be cut out by frieze excavation on the hillside at the elevation of 3 m, of 25 x 30 m. The wall could be in a terrace form upon which will be built a small tower for the reception of the direct current to the pump motor and the departure of the alternating current produced.

As the granite rock is impermeable and of most limited porosity, less than 0.5%, damaging infiltration will not be found along the walls of the excavation. The floor of the station will be at an elevation of 3 m, and toward the sea it will be protected by a sturdy parapet whose outer side is shaped in such a way as to repel the waves.

For the installation of the pumps, as the hillside is almost ridge-like, a trench will be dug down to 2 m, which will be cistern-shaped and adequate in capacity and depth, and into which will be installed the pumps which will have a minimum intake and will be able to function even at very low velocities, if they are of the piston type, as we propose.

For access to the station, it will be easy to build along the shore a connecting road to the Giglio harbor, which lies at a distance of about 400 m.

For access to the basin, as has been stated, a passable road is provided. The footpath which, from the north end of the inhabited area of Giglio harbor, leads to the passable road, then runs through the bottom of the small valley toward the basin and later veers conveniently uphill.

The full pipe conduit will be in reinforced concrete of the Vianini system and will have a diameter of 0.80 m. The normal pressure will be 10.5 atm. It will, however, be calculated in 20% excess to take into account possible battering by drop hammers. Given its short length, there will be no necessity of a piezometric wall.

Being required to anticipate a capacity at least four times as large as that used for production, when the output power exceeds 500 kW, i.e. $2.4 \text{ m}^3/\text{sec}$, the maximum velocity will be $2400/0.5 = 4.80$. With $R = 0.20$ and 0.10 being the roughness coefficient guaranteed by Vianini, it works out to $C = 75.1$ for this capacity. We will then obtain:

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from which

$$4.80 = 75.1 \sqrt{0.20 \cdot i}$$

$$\sqrt{i} = \frac{4.80}{75.1 \cdot \sqrt{0.20}} = 0.143$$

and $i = 0.0204$.

As the conduit is about 360 m long, there will be a load loss of approximately 7.20 m for the maximum capacity in ascent.

When the conduit is only functioning in descent to supply the power station, the load loss becomes one sixteenth of the above, which is only 0.45 m.

With regard to the station, as the average head is 95 m, we will use for the turbine a Francis model with 612 effective hp, and an alternator with a power output of 562 kVA. Special methods will have to be adopted for the design and functioning of the pump which must increase its capacity with a rise in available power and, inversely, stop its action with a drop below a certain limit in power, down to a complete standstill.

For this purpose, one must adopt a piston pump, whether for the sake of high efficiency which is constant at any velocity, or for the sake of its irreversibility at times when it must stop due to insufficient energy.

Indeed, during calm when wind energy drops, the station will be fed completely or partially by the reservoir basin.

The location selected for the full pipe conduit and the power station is very favorable for pumping water because the rocky slope descends in a ridge down to beyond 10 m below sea level, and therefore there will be no danger of pumping in sandy water, as the rocky bottom is free of any soil deposits.

Again regarding the basin, it will always be possible to increase the capacity later, whenever a necessity may present itself to increase the power output of the plant. In fact, at the upper end of the planned basin there is a saddle at elevation 107 m, and the excavation could be extended into this even as far as a relief which is located to the northeast.

In addition to the water pumped from the sea, one could add the water from rainfalls which, although scarce, still reach around 500 mm/year; these can supply a considerable amount if they are collected by a trough of adequate length, which would intersect some of the numerous vales that furrow the slopes of the island.

The other solution mentioned in regard to energy accumulation and illustrated in Figs. 9, 9a, 9b and 9c was also considered. With this solution, the water basin would be built over the Allume bay, where a dike 24 m high would create a cistern of about 1 million m³. Furthermore, the full pipe conduit would be much shorter, because the head would be reduced to an average of 72 m.

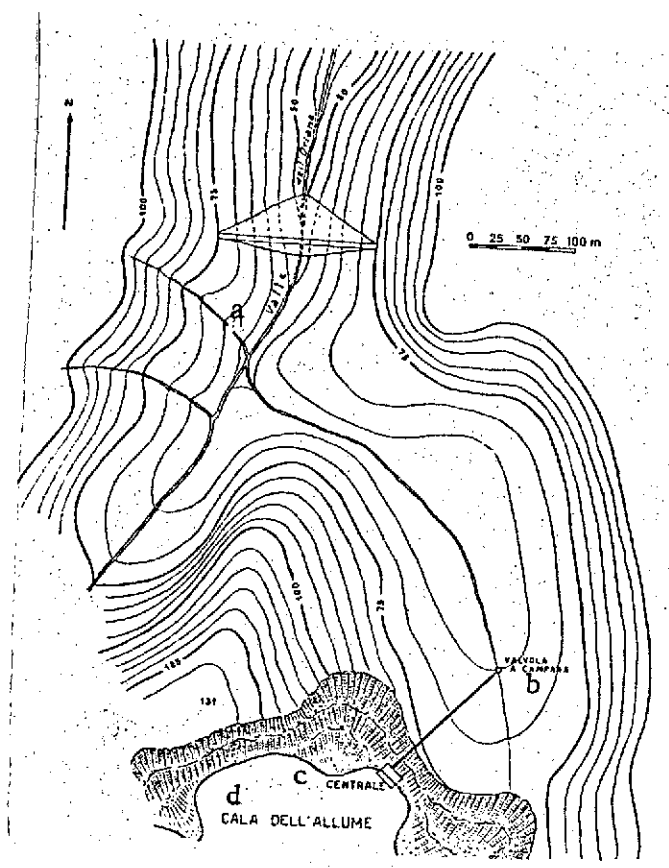


Fig. 9. Topography of the accumulation basin, full pipe conduit and the station in the second solution (bay of Allume).

Key: a. Valley of Ortana
 b. Bell-type valve
 c. Power station
 d. Bay of Allume

The executive office will investigate the suitability of this solution which, as stated, has caused hesitations due to the nature of the soil which is not all granitic as in the eastern parts of the island. In fact, the valley of Ortana, which must be utilized for creating the cistern in it, closely follows the line of contact between the granite formation and the limestone formation of the western side. Furthermore, the distance from Giglio harbor is much greater, but the transportation of materials and machinery could be conducted by way of the sea, as the bay of Allume is already equipped for receiving and sending goods and materials.

From an investigation conducted on the cost of the work, it emerged that the expense is appreciably the same as that of the previous solution.

Connection of a Direct-Current Generator System to the Air Motor

Following experiments conducted at the Galileo Ferraris National Electrotechnology Institute in Turin, the feasibility

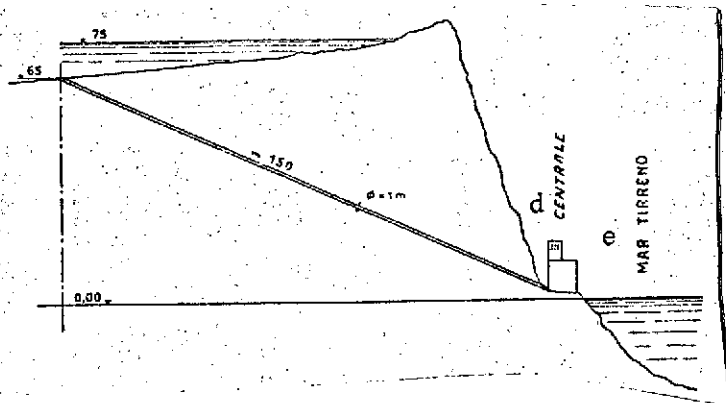
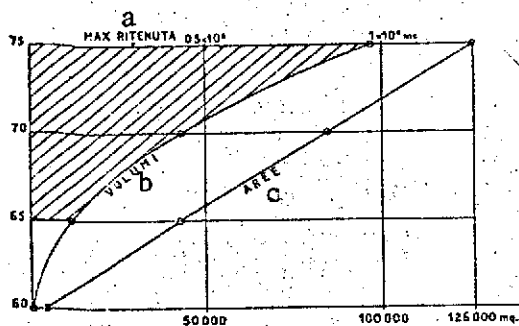


Fig. 9a. Diagram of the volumes of the cistern and full pipe conduit in the second solution (bay of Allume).

Key: a. Max. retention
b. Volumes
c. Areas
d. Power station
e. Tyrrhenian Sea

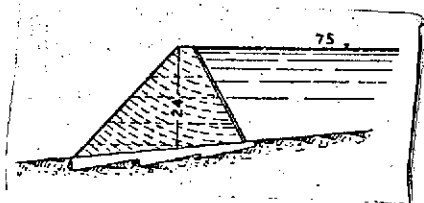


Fig. 9b. Section of the rock-filled dike in the second solution.

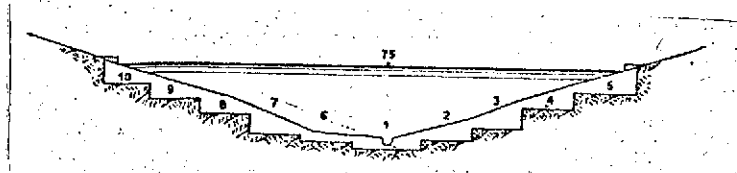


Fig. 9c. Elevation of the rock-filled dike in the second solution.

was demonstrated of constructing direct-current generator sets (two half-dynamos, or two dynamos with one exciting the other) which, driven by air motors, are capable of producing electrical energy of practically constant voltage within quite extended limits of variation in the speed of the first motor.

As revealed by the report published on the question in the journal Elettrotecnica by Prof. A. Carrer [1], the electrical energy produced can be immitted for its

utilization into a main power network, and in order to do this, it is necessary to conduct suitable regulation of the properties of the energy itself. First of all, it is necessary to operate the regulation of the voltage produced by the generator, which could take place by regulating the pilot voltage. The regulator must be sensitive to the speed of the electricity generator, and for every speed it must be capable of varying the voltage in the correct direction, until the generator is no longer giving out the power which, excluding losses, can be supplied to it by the first motor. The generator must be adjusted so that it can support the maximum current load which is obtained at the fastest speed, i.e., as has been seen, 2000 kW.

Of all possible schemes, the one containing two dynamos of regular type appears to be the most suitable, because with this, the electrical generator can produce a voltage which is practically constant within very wide limits.

Another solution was also proposed by Engineer Dario Morbiducci and tested by Prof. Carrer at the Galileo Ferraris Electrotechnology Institute [2], in case the three-phase network which is unlike the present systems should come into existence. This solution would permit the aforementioned exclusion of the pumps when the wind velocity is sufficient for the production of alternating current for immission into the main three-phase network. It involves an electrical scheme using the same devices as those which constitute a Ward-Leonard system but opposite in function, i.e. prescribing the normal defluxion of the energy from the direct current circuit to the three-phase network, rather than from the three-phase network to the direct-current circuit.

Lastly, according to the proposal by Prof. Antonino Asta [3], one can use, in this case more generally, a mercury vapor converter

functioning as an inverter, by connecting the direct-current device across it with a three-phase network, which is maintained at constant voltage by its own synchronizer.

The experimental data obtained both by the combination of direct-current generators and by the inverted Ward-Leonard scheme enabled the deduction of the characteristics to be adopted in the different devices and also allowed us to prescribe the mounting of the air motor on the same shaft as the main generator. Thus, in the experiment for the combination of two dynamos for example, which was presented in the report cited, the main dynamo's speed worked out to 450 rpm, and therefore close enough to that calculated for the air motor proposed for the plant. For the velocities of weaker winds which, as has been seen, become notably higher in the Venturi tube, it will be necessary to prescribe a connection of the kind that would allow going from low speeds of the air motor to the minimum allowable speeds for the dynamo.

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Regulation System for the Air Motor

As noted in the functioning of the air motor in free air, maximum aerodynamic efficiency is subordinate to the constancy of the relationship u/v , which is to say of the peripheral speed of the blades to the wind velocity. In the type of high-speed air motor with three blades and variable angles of incidence shown in Fig. 5, the characteristic diagrams were presented for the values of the power coefficients $C_p = P_v/qSv$, in the moment of rotation $C_r = M_r/qSR$, and of the axial thrust $C_s = R/qS$ as a function of the relation u/v , as obtained from tests in the wind tunnel of the Göttingen Institute.

In the same figure above, diagrams were traced in dotted lines for a particular value of the angle β on which depends the

angle of incidence of a given section, and in a continuous line the curve enveloping the above diagrams for variable β was traced.

From the figure it is easy to take note that, assuming the number of revolutions to be constant, the increase in the coefficient C_p with respect to the case of blades mounted at a fixed angle of incidence is quite considerable, especially for the larger values of u/v , i.e. for the low velocities of hardly exploitable winds.

For velocities higher than the normal value, i.e. those of greater efficiency, the coefficient, and thus the effective power, drop rapidly to minimal values in correspondence with values of the u/v relation which are lower than the optimal values contained between 4 and 6 that are valid for high-speed air motors. The sector of work of the air motor for high velocities would then be almost entirely lost, necessarily due to the relation u/v , for constant u and increasing v , assuming values lower than 4 and diminishing consequently the coefficient C_p along the descending leg of the enveloping curve, whatever the value of β or of the angles of incidence. Also, for the work sector of $u/v > 6$, which will occur for values of v below the normal value, the coefficient C_p will work out, even with the mentioned improvement regarding blades of fixed angle of incidence, to be always lower than the value corresponding to the relation u/v contained between 4 and 6.

From the preceding paragraph, one clearly sees the necessity of varying the number of revolutions of the air motor according to the wind velocity, if one wishes to maintain for all wind behavior conditions the maximum efficiency of the air motor itself. As was seen earlier, this variation will not cause a detectable variation in the voltage of the direct current produced (at least within certain limits, besides those wide enough to contain all possible oscillations in wind velocity in the field of wind energy

utilization);and its regulation could be easily conducted by shunting the excitation winding in series in the set of two dynamos proposed.

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Next comes the following scheme for the regulation of the air motor, assumed for the moment to have fixed blades. The functioning of a regulator driven directly by a wattmetric disk would be immediate, if only the relation u/v were influenced in the variation of the air motor power. But, as is known, this varies even at the rate of the cube of the wind velocity, and will thus require a distinction between the following possible phases of regulation.

In the case where the wind velocity increases, there will certainly be a diminution of the relation u/v , and therefore a reduction of the coefficient of power C_p along the forward descending leg of the diagram concerned, as a function of u/v ; but when the air motor power increases at the rate of the cube of the wind velocity, the increase will have prevalence over the diminution of the coefficient C_p and the regulator will intervene, shifting the shunt brushes on the turns of the excitation coils in such a way as to increase the speed of the generator.

From this will be derived an increase in the relation u/v up to the point of the optimum value for which the air motor has been calculated. If the wind velocity should stabilize in the meantime, the position of the brushes set by the regulator would be just at the point which gives the maximum power extractable from the air motor for that given wind velocity, and the regulation phase would be terminated. But given the inertia of the air motor-generator unit, which will take a certain amount of time to be overcome, this position will certainly be surpassed, and the relation u/v will increase to bring the coefficient C_p to values still smaller along the rear descending leg of the diagram,

until another intervention of the regulator is caused, through the subsequent power reduction, this time in the direction opposite to that of the previous case, i.e. in such a way as to slow down the speed of the generator. There will then be the position of nonintervention of the regulator, when the relation u/v will thus have reached the optimum value and the air motor power the maximum for that value already established by the wind velocity.

Conversely, in the case where the velocity decreases, there will in the meantime be a sudden and strong reduction in power to the measure of the cube of the wind velocity; at the same time, however, the relation u/v will increase, and thus the coefficient C_p will diminish along the second descending leg of the diagram, contributing also to the power reduction. The wattmetric regulator will then intervene to shift the brushes in such a way as to reduce the generator speed, and the relation u/v will diminish to make the coefficient C_p rise again toward the optimum value, which, however, will not be surpassable this time, due to the prevalence of the power reduction, which is at the rate of the cube of the wind velocity, with respect to the increase in the coefficient that varies only linearly with the wind velocity. When the latter has stabilized, the regulation phase will end with the attainment of the maximum in the coefficient C_p in correspondence with the optimum value of the relation u/v .

The function of the regulator in this second case was therefore that of bringing, without delay, the number of revolutions of the generator to the optimum value (isodrome regulator), while in the first case it tended to stabilize the number of revolutions at a value slightly higher than the optimum (hyperisodrome regulator); but with the intervention of automatic compensation, or autocontrol, it was brought down to the optimum value.

Regulation can be achieved, for instance, with a U-shaped tube containing mercury and mounted tangentially on the wattmetric disk, on which will work an amperometric coil inserted in the line connecting with the generator and a voltmetric coil originating from the same line, electromagnetically imparting to them a speed proportional to the power given out, with zero acceleration corresponding to the maximum power, positive acceleration for increasing power, and negative acceleration, or deceleration, for decreasing power.

Another type of accelerometer⁵ produces an entirely electrical solution of the problem, which seems better adapted to the small values of the variations in the forces at play. One may imagine that the wattmetric disk drags in rotation a small suspended mass, by means of opposing springs; this mass is free to undergo a tangential shift in one direction or the other through the action of the force of inertia deriving from the speed variation.

If one of the springs is substituted by a series of some 100 fine wires stretched between the mass and the disk, and its elastic constant is given by 100 times the constant of each of the wires, when these are connected electrically one after the other, the series system would be subjected to additional traction stresses, positive or negative, proportional to the actual accelerations, while the tension of the stretched spring opposite will be affected very little by the corresponding variations. If the system itself has electrical current going through it, there will be voltage variations at the extremities, which are proportional to the variations in electrical resistance caused by the different traction stresses to which the wires are subjected.

⁵R. Vezzani, Italian patent, "Electrical device for measuring centrifugal force or acceleration in centrifugal or wattmetric regulators, or in accelerometers, seismographs, speedometers, stroboscopes and other instruments.

Supposing, for example, that the mass consisted of a small cylinder on solid iron, 4 cm in diameter and height, and that on one of the pairs of yokes which hold it in place on the disk (the other pair is attached by two spiral springs in tension), is wound a constantan wire 0.05 mm in diameter for 50 turns in the manner of inserting therein a system of 100 parallel wires whose action is opposite to that of the other pair; the accelerometer thus arranged would have its own oscillation of 200 Hz, and the tension of the two groups would become equal at about three times the weight of the mass and one-sixth the safety load of the wires. This, apart from being safe enough mechanically, would be capable of measuring oscillations up to three times the acceleration of gravity, while toward zero, the field of sensitivity would cover accelerations of $1/1000 \text{ cm/sec}^2$.

The variations in electrical resistance of a similar accelerometer would be about 1 ohm for accelerations in the magnitude of that of gravity. The system of wires would be capable of having a current of 50 mA running through it. There is thus the possibility of employing the regulator apparatus without resorting to an amplifier, since for moving the brushes it would suffice to adopt differential relays of the types in use in the technology of weak currents.

From the numerical example given above, it is deduced in addition that in wind gusts that are stronger and more sustained, for an average duration of 7 sec which is the one most observed with high wind velocities, the duration of the oscillations in the speed of the generator connected to the air motor turns out to be effectively much shorter than that indicated above. For this reason, there are, in the rotation speed and therefore also in the power output of the air motor-generator unit, periodic oscillations due to gusts, which will have to be regulated if the dangerous resonance phenomena are to be avoided. This is why it

is necessary to use a strongly damped regulator, similar to the one described above, whose own oscillation does not distort the accelerometer detections, as often happens for such instruments when the oscillatory phenomenon includes isolated movements in the form of knocks.

From what has been expounded so far, therefore, the perfect /418 correspondence to the required qualifications emerges, whether theoretical or practical, for the proposed regulation system, even in the rather frequent case of strong and sustained gusts, because in fact for the fastest and easiest maneuvering of the shunt brushes, the small fractions of a second necessary to vary the power output from the generator under the thrust of the gust are sufficient, since all other operations required for this occur electrically. Furthermore, even a considerable delay in the regulation of the generator upon the instantaneous variation of the wind will not produce, as in the case of blades that are controllable for maintaining a constant number of revolutions, damaging overloads and overheating of the generator; but at most, a lowering of the air motor efficiency during only the extreme peaks of the gusts.

What has been developed up to this point presupposes, as we have stated, that the air motor blades are set rigidly on the rotation shaft, i.e. angles γ and β are fixed. But as with Kaplan turbines, in order to create the conditions of maximum efficiency for widely diverging values of velocity and therefore of the capacity of the fluid, the blades should be revolvable on their own axis perpendicular to the axis of rotation, so that their shift would enable the variation of incoming and outgoing angles of the velocity of the air current.

As for the means necessary for this, we can refer to regulators of the ordinary type for such turbines, i.e. the control mechanisms

contained in the nave of the blades. Control is then automatic or manual with devices suitable for ensuring the correct setting of the blades with respect to the wind velocity, measured with a suitable anemograph installed in a convenient position. Although this second regulation method which, based on mechanical or even automatic devices, is necessarily slower than the first one effected entirely with electrical devices, it will be possible to follow slower variations in the average wind velocity, i.e. what occurs at the median line of the maximum and minimum velocities of the gusts according to the signals from anemographs, which are designed to eliminate these oscillations, and which are now offered on the market (mechanical or electrical devices of the Richard type). By combining these two regulation methods, one can thus obtain a perfect response of the blade setting for every instantaneous velocity of importance, and therefore always the maximum air motor efficiency.

Cost Estimate of the Plant

On the basis of the works described and current cost of materials and labor on the island of Giglio, the cost of the wind-electric plant was calculated as follows:

1.	Basin -- open excavation of 90,000 m ³ @ 500 lire	45 million
2.	Rock-fill retention dike, 60,000 m ³ @ 500 lire	30 "
	Diaphragm dike, approx. 2700 m ² , average thickness 0.50 at 20,000 lire/m ³ per 1350 m ³	27 "
3.	Gallery for pipe laying, 200 m; section 2 m ² = 400 m ³ at 5000 lire/m ³	2 "
4.	Full pipe conduit 0.80 ø 360 ml at 20,000 lire	7.2 "
	Open excavation for laying full pipe 150 x 1 x 2 ml = 300 m ³ at 1500 lire	0.45 "
5.	Open excavation for small square for the power station 1/2 31 x 15 x 30 m ³ = about 7000 m ³ at 1000 lire	7 "
6.	Excavation of trenches for laying pump, in oblique section 30 x 3 x 1 = 90 m ³ at 2000 lire/m ³	0.18 "

7.	Power station: structure 7200 m ³ at 5000 lire	36 million
	Pump motor 2000 kW at 10,000 lire/kW	20 "
	Pump, max. 2400 liter/sec and h = 115 m	10 "
	Alternator, 562 kVA	5.62 "
	Francis turbine of 612 effective hp	5 "
	Panel and equipment	2 "
8.	Wind motor and related structures	100 "
9.	D.C. dynamo with special excitator, 2000 kW	20 "
10.	D.C. line from Pagana to the station, 2.5 km at 300,000 lire/km	0.75 "
11.	A.C. line for connection to network, 1 km	0.50 "
12.	Access road to station 400 ml at 3000 lire/ml	1.22 "
	Incidentals, expenses and 10% financing	30 "
		<hr/> 350 million

Production 2,300,000 kWh; cost per unit $350/2.3 = 152$ lire

Cost of 20% kWh production = 30.40 lire.

The present cost on the island of Giglio of the energy produced thermically with generator sets, and supplied only for a few hours in the evening, is 84 lire/kWh, which, increased by the premium imposed by the compensation fund for thermic energy, represents an effective cost of 100 lire/kWh.

For making a comparison with other wind-electric plants of the conventional system with large air motors exposed to free air, we will refer to the following German project which, however, was abandoned after the war.

The total cost of a Honnef-type wind-electric plant with three wheels 160 m in diameter for 22,000 kW installed power and 14,400 kW average power per year, in 1934, was calculated as follows in Germany:

a) Construction site, access roads and foundations	390,000 marks
b) Frame and air motors	2,900,000 "
c) Main costs for machinery	370,000 "
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	3,660,000 marks
d) Hoists, lifts and stairs	200,000 marks
e) Extras for moving parts, repair shops, measuring equipment, transformers, etc.	640,000 "
	<hr/>
	4,500,000 marks

Cost of the Power Plant

f) Capital services	355,000 marks
g) Maintenance and operation costs	50,000 "
	<hr/>
	405,000 marks

Annual Expense

Taking into account the losses through generators, current transformation and energy transmission, there remain available for the users 12,000 kW which would mean an annual production of 105 million kWh. Of this energy, only 54% could be considered saleable to the user, which is to say 57 million kWh. The costs of the plant per wind-electric unit thus amount to:

a) Cost of the plant for installed power	208 marks/kw
b) Cost of average produceable power per year	312 "
c) Cost of average power yielded	375 "
The production cost of total energy produced	0.32 pf./kWh
The production cost of saleable energy	0.386 "
The production cost of energy sold	0.71 "

These figures must be multiplied by 4.53 lire, which was the exchange rate for a Reichsmark of that period, and then by about 60 lire, to reduce the value of that time to the present lira. We thus get the following present-day costs:

a) Cost of the plant for installed power	56.160 lire/kW /419
b) Cost of average produceable power per year	84.240 "
c) Cost of average power yielded	101.220 "
d) The production cost of the energy produced	8.64 lire/kWh
e) The production cost of the energy to distribute	10.44 "
f) The production cost of saleable energy	31.95 "

In the description of another German project for another wind-electric power plant of the "Kleinhenz" type, MAN-BBC with a capacity of 10,000 kW, it was mentioned that a giant wind-electric power station economically came between a coal power plant and a hydro-electric plant, and that, due to savings in coal and smaller operation costs, it presented notable advantages.

The project by the U.S. Federal Energy Commission for an installed power of 7500 kW would cost, according to a report in the Electrical World journal in New York, April-May 1945, from \$68 to \$70 per kW installed, which is, given the current exchange rate of 630 lire/dollar, 44,000 lire/kW.

For the operation cost of the energy produced, they considered the case of five adjacent plants requiring 11 operators, one chief technician and an assistant, and the production of energy was estimated as 98% (2% for the normal period of nonoperation for repairs and inspections) of that obtainable with a 50% load factor in a series of interconnected networks having a high total capacity and stabilization with water storage. In this case, the energy produced by wind came to cost from \$0.000134 to \$0.000204 per kWh, for which the fixed tax was 6 or 10.5%. Assuming the second figure, we would get the present-day value of 1.2 lire/kWh at the exchange rate indicated above. This is the cost only for operation that is exceptionally favorable due to the interconnection between plants. On the other hand, calculating the

total cost by the previous method, we get, for energy to be distributed, 8 lire/kWh, and for saleable energy, about 24 lire/kWh.

These cost comparisons therefore reveal the convenience, from the economic point of view as well, of a wind-electric power plant of the new type with the Venturi tube, in comparison with the ordinary type with tall metal support frames and giant air motors, if one also takes into account the feasibility of its meeting the normal energy requirements, by itself, even during long summer periods of weak winds, which were not anticipated in the other plants.

Summary

Having summarized the new project instructions for a 500-kW air motor pilot plant on the island of Giglio (Grossetto Province), which aim at concentrating wind energy in space through the adoption of a Venturi tube and at increasing the depression in the narrow passage (where the air motor is mounted) by means of static air exhausts installed at the mouth of its outlet, one determines the plant's power and the energy extractable in an average year on the basis of the existing anemological data of the area going back about 20 years, and on the basis of calculation methods collated with experimental data obtained in tests carried out in a wind tunnel on the models of the various component parts of the plant.

The project, which is now being studied by the High Council of Public Works, is completed by the study of the accumulation of energy produced by two continuous-current, fixed-voltage generators through pumping sea water into a basin obtained by damming a granite rock-formation valley on the island with a dike, as well as by the instructions to be adopted for the regulation of the wind-electric plant, whether by means of varying the angle of

incidence of the air motor blades, or by means of shunting the excitation coils of the excitation dynamo conducted by a special accelerometric control given by a wattmetric disk. Lastly, the cost estimate for the whole plant is analyzed in comparison with that of other conventional power plants planned in Germany and in the USA.

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